THE DEPARTMENT OF DEFENSE

CRITICAL TECHNOLOGIES PLAN

FOR THE COMMITTEES ON ARMED SERVICES UNITED STATES CONGRESS

15 MARCH 1990

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Appendices

EXECUTIVE SUMMARY

The second Annual Defense Critical Technologies Plan responds to Public Law 101-189 of November 29, 1989, which requires the Secretary of Defense to submit to the Committees on Armed Services of the Senate and House of Representatives an annual plan for developing the technologies considered by the Secretary of Defense and the Secretary of Energy to be the technologies most critical to ensuring the long-term qualitative superiority of United States weapon systems.

The plan was developed by a working group chaired from the Office of the Secretary of Defense (OSD), with representatives from Army, Navy, Air Force, the Strategic Defense Initiative Organization (SDIO), Defense Advanced Research Projects Agency (DARPA), Defense Nuclear Agency (DNA), Defense Intelligence Agency (DIA), OSD Offices, Department of Energy (DoE) Headquarters, and National Laboratories (Los Alamos, Livermore, and Sandia). Nuclear technologies were not included in this document because they represent a critical range of research and development reserved for separate discussion. Nuclear effects are included to the extent that their consideration is important in the development of the critical technologies described herein. The Department of Energy is preparing a separate annex that addresses nuclear technologies. This annex will be submitted at a later date.

The report selects 20 critical technologies. The selection process is described, criteria for selection are set forth, and industrial and international assessments are summarized. The following critical technologies (not shown in priority order) were selected.

- Semiconductor Materials and Microelectronic Circuits
- Software Producibility
- Parallel Computer Architectures
- Machine Intelligence and Robotics
- Simulation and Modeling
- Photonics
- Sensitive Radars
- Passive Sensors
- Signal Processing
- Signature Control
- Weapon System Environment
- Data Fusion
- Computational Fluid Dynamics
- Air-Breathing Propulsion
- Pulsed Power
- Hypervelocity Projectiles
- High Energy Density Materials
- Composite Materials
- Superconductivity
- Biotechnology Materials and Processes

These technologies were selected as critical ones by a group of senior DoD officials with responsibility for the Science and Technology (S&T) program, based on the recommendations of the working group. The plan was coordinated throughout DoD. In response to direction from the Congress, the technologies were prioritized into three groups. Those judged to be of first priority were placed in Group A; second, Group B; and the remaining ones, Group C. Since these 20 critical technologies are already those selected as "most essential" from the great many more which constitute the total S&T program, the further prioritization should not be overemphasized. Table 3 on page 7 of the plan lists the three groups. Significantly, those in Group A are the most pervasive technologies; those in Group B, enabling technologies which offer the most immediate advances in weapon systems capabilities; and those in Group C, principally emerging technologies whose applications are farthest in the future and most difficult to identify in detail at this time.

The Congress also asked that the critical technologies be placed in context with the total S&T program. This is done in the DoD S&T Investment Strategy which is published for the first time this year in a separate report. If this report is found useful, we will suggest that it replace the Critical Technologies Plan which is contained within.

Several useful meetings were held with representatives of the Aerospace Industries Association (AIA), the Electronic Industries Associations (EIA), and the National Security Industrial Association (NSIA) to discuss ongoing activities in strategic planning for science and technology in industry and in DoD.

The major portion of this report is contained in 20 sections in Appendix A, one section for each critical technology. Each section addresses the questions posed by Congress on funding, plans and milestones, industrial base and manufacturing issues, and the competitiveness of US industry; it also provides an assessment of the positions of the Soviet Union, NATO, Japan, and other industrialized countries in niche technologies within each critical technology. Table 5 on page 11 summarizes foreign technological capabilities in all 20 critical technologies. Types of international technology exchange agreements are summarized; specific examples are given in each technology section in the appendix that follows.

The report reflects combined DoD and DoE efforts to respond to Congressional interest in these and other related issues in defense science and technology.

DEFENSE CRITICAL TECHNOLOGIES PLAN

"Where there is no vision, the people perish."

(*Proverbs*, 29: 18)

A. INTRODUCTION

The second Annual Defense Critical Technologies Plan responds to Public Law 101-189 of November 29, 1989, which requires that "the Secretary of Defense shall submit to the Committees on Armed Services of the Senate and House of Representatives an annual plan for developing the technologies considered by the Secretary of Defense and the Secretary of Energy to be the technologies most critical to ensuring the long-term qualitative superiority of United States weapon systems." The 20 critical technologies that were selected are described in Appendix A. The applicable part of the law is reproduced in Appendix B. Since submission of this plan follows closely the President's budget submission for Fiscal Year 1991, the plan is referred to as the FY 1991 plan.

The plan was developed by a working group chaired from the Office of the Secretary of Defense (OSD), with representatives from Army, Navy, Air Force, the Strategic Defense Initiative Organization (SDIO), Defense Advanced Research Projects Agency (DARPA), Defense Nuclear Agency (DNA), Defense Intelligence Agency (DIA), OSD Offices, Department of Energy (DoE) Headquarters, and National Laboratories (Los Alamos, Livermore, and Sandia). Nuclear technologies were not included in this document because they represent a critical range of research and development reserved for separate discussion. Nuclear effects are included to the extent that their consideration is important in the development of the critical technologies described herein. The Department of Energy is preparing a separate annex that addresses nuclear technologies. This annex will be submitted at a later date.

Congress asked that the critical technologies be placed in context with the total S&T program. All technologies are related in the DoD S&T Investment Strategy which is published for the first time this year in a separate report.

Congress requested the amounts in the DoD and DoE budgets for the support of the development of each critical technology. Funding for each technology is derived from many programs in the DoD and DoE budgets. Since most programs involve several technologies, determining how many dollars to count toward any one technology becomes a matter of judgment. The funding presented throughout this report, for each critical technology, is of the right order of magnitude but should not be construed as a precise budgetary quantity.

Milestones for each technology are presented in a separate table for each critical technology (Appendix A). These milestones are visions of where the technology could be 5, 10, and 15 years from now.

Industrial base and manufacturing issues are addressed in Appendix A for each critical technology. Each section contains an assessment of the positions of the Soviet Union, NATO, Japan, and other industrialized countries in niche technologies within each critical technology, including a summary table for that technology.

Finally, it should be noted that the term "critical technology" is used herein in the sense of PL 101-189 (quoted in the opening paragraph above) and should not be confused with "militarily critical technologies" as applied to technology export control.

B. THE DOD SCIENCE AND TECHNOLOGY INVESTMENT STRATEGY

The critical technologies are contained in the technology areas of the S&T Investment Strategy which is published for the first time this year in a separate report. The investment strategy describes the total S&T program both in a set of 14 functional or military mission areas and in a set of 17 technology areas. The relationship of the critical technologies to these technology areas is addressed in the S&T Investment Strategy.

The investment strategy develops a Strategic Plan derived from the National Military Strategy, published by the Office of the Joint Chiefs of Staff, and the Defense Planning Guidance, published by the Office of the Secretary of Defense. The plan also considers the impact of changing security, economic, and technological environments. Twelve major long-term goals were derived from vision statements of needed military capabilities 15 to 20 years in the future. The major long-term goals are listed in Table 1. Approximately 200 technical objectives support the achievement of the goals. The critical technologies represent a judgment as to the 20 most important weapon-related technologies. Table 2 shows the linkage between the goals and the 20 critical technologies. The pervasiveness of some technologies is demonstrated by the fact that they support all 12 goals, as shown by the lines in the table.

Table 1. Major Long-Term Goals of the Investment Strategy

DETERRENCE	
Goal 1.	Weapon systems that can locate, identify, track, and target strategically relocatable targets.
Goal 2.	Worldwide, all-weather force projection capability to conduct limited warfare operations (including special operations forces and low intensity conflict) without the requirement for main operating bases, including a rapid deployment force that is logistically independent for 30 days.
Goal 3.	Defense against ballistic missiles of all ranges through non-nuclear methods and in compliance with all existing treaties.
MILITARY SUPERIORITY	
Goal 4.	Affordable, on-demand launch and orbit transfer capabilities for space-deployed assets with robust, surviable command and control links.
Goal 5.	Substantial antisubmarine warfare advantages the United States enjoyed until recent years.
Goal 6.	Worldwide, instantaneous, secure, survivable, and robust command, control, communications, and intelligence (C3I) capabilities within 20 years, to include: (a) on-demand surveillance of selected geographical areas; (b) real-time information transfer to command and control authority; and (c) responsive, secure communications from decision makers for operational implementation.
Goal 7.	Weapon systems and platforms that deny enemy targeting and allow penetration of enemy defenses by taking full advantage of signature management and electronic warfare.
Goal 8.	Enhanced, affordable close combat and air defense systems to overmatch threat systems.
Goal 9.	Affordable "brilliant weapons" which can autonomously acquire, classify, track, and destroy a broad spectrum of targets (hard fixed, hard mobile, communications nodes, etc.).
AFFORDABILITY	
Goal 10.	Operations and support resource requirements reduced by 50 percent without impairing combat capability.
Goal 11.	Manpower requirements reduced for a given military capability by 10 percent or more by 2010.
Goal 12.	Enhanced affordability, producibility, and availability of future weapons systems.

Table 2. Major Linkages Between Critical Technologies and Major Long-Term Goals for the S&T Program

Critical Technology \ Goal	1. Strategically Relocatable Targets	2. Force Projection/Rapid Deployment	3. Defense Against Ballistic Missiles	4. On-Demand Space Asset Deployments	5. Antisubmarine Warfare	6. Worldwide, All-Weather C3/Surveillance	7. Signature Management	8. Close Combat/Air Defense	9. Brilliant Weapons	10. Reduced Support Requirements	11. Personnel Reduction	12. Affordable/Producible Weapon Systems
1. Semiconductor Materials and Microelectronic Circuits	◄											►
2. Software Producibility	◄											►
3. Parallel Computer Architectures				X		X			X	X		
4. Machine Intelligence and Robotics				X				X	X	X	X	X
5. Simulation and Modeling		X				X		X		X	X	X
6. Photonics						X			X			X
7. Sensitive Radars	X		X		X	X		X	X			
8. Passive Sensors	X		X		X	X		X	X			
9. Signal Processing	X		X	X	X	X			X		X	
10. Signature Control	X		X		X		X					
11. Weapon System Environment	X	X	X		X			X	X			
12. Data Fusion	X		X	X	X	X				X	X	
13. Computational Fluid Dynamics				X	X			X				X
14. Air-Breathing Propulsion		X		X			X	X		X		X
15. Pulsed Power			X					X				X
16. Hypervelocity Projectiles			X					X	X			X
17. High Energy Density Materials			X	X				X		X	X	X
18. Composite Materials	◄											►
19. Superconductivity			X		X	X				X		
20. Biotechnology Materials and Processes										X	X	X

C. SELECTING THE CRITICAL TECHNOLOGIES

This section presents the criteria used for selecting the 20 critical technologies, which are then listed and prioritized.

1. Criteria for Selection

The critical technologies selected must meet the following criteria:

Performance Criteria

- Enhancing performance of existing weapons systems
- Providing new military capabilities

Quality Design Criteria

- Contributing to availability, dependability, reliability
- Contributing to weapons systems affordability (lower life cycle cost through producibility, maintainability, etc.)

Multiple Use Criteria

- Pervasiveness in major weapon systems
- Strengthening the industrial base

For a technology to be considered critical, major improvements in one or more selection criteria are sought. (As a guide, improvements by a factor of three in some performance parameters are considered appropriate.) The first four parameters are the same as in last year's plan; the last two criteria have been added this year, one of them to reflect explicitly the growing concern for spin-off to the industrial base.

2. The Selected Critical Technologies

The following 20 critical technologies were selected. (They are not shown in order of priority.)

- Semiconductor Materials and Microelectronic Circuits
- Software Producibility
- Parallel Computer Architectures
- Machine Intelligence and Robotics
- Simulation and Modeling
- Photonics
- Sensitive Radars
- Passive Sensors
- Signal Processing
- Signature Control
- Weapon System Environment
- Data Fusion
- Computational Fluid Dynamics
- Air-Breathing Propulsion
- Pulsed Power
- Hypervelocity Projectiles
- High Energy Density Materials
- Composite Materials
- Superconductivity
- Biotechnology Materials and Processes

Fifteen titles remained the same as they were last year: software producibility, parallel computer architecture, machine intelligence/robotics, simulation and modeling, sensitive radars, passive sensors, signature control, data fusion, computational fluid dynamics, air-breathing propulsion, pulsed power, hypervelocity projectiles, composite materials, superconductivity, and biotechnology.

The following changes have been made since the preceding plan:

- Two of the technologies are combinations of pairs of closely related technologies under one title: *semiconductor materials and microelectronic circuits*, and *photonics* (combining *integrated optics* and *fiber optics* from last year's list with emphasis on optical information processing).
- *Signal processing* replaces *automatic target recognition* (ATR), which is better characterized as a critical need and is included under *signal processing*, a critical technology.
- Two titles were removed from the list, but aspects of the technology are included elsewhere: *high power microwaves* under *pulsed power* and *phased arrays* under *signal processing* and *sensitive radars*.
- Two new technologies were introduced: *High energy density materials* is concerned with improved explosives for munitions, and with improved propellants for rockets. *Weapon system environment* was omitted last year because it is not an identifiable component of a weapon or other military system. It does, however, influence weapon system design and contributes materially to the "long-term qualitative superiority" of US weapon systems.

It is advantageous to describe each critical technology in terms of technology challenges which may be expressed in terms of products, processes, tools, or capabilities to be developed. The 20 critical technologies and the technology challenges that have been set for each one are presented in Appendix C. The role of defense in the development of these technologies is also summarized there.

3. Prioritizing the Critical Technologies

The priorities assigned to the 20 critical technologies are based on judgments from the working group that selected the technologies and inputs from a number of defense industrial contractors. The final judgment on assigning the critical technologies into three priority groups was made by a senior committee representing individuals in the DoD and DoE with management responsibility for the S&T program. Table 3 shows the result, where Group A contains the highest priority technologies, followed by Groups B and C.

(Note that within each group the technologies are listed in alphabetical order and do not reflect priorities within each group.) Significantly, those in Group A are the most pervasive technologies; those in Group B, enabling technologies which offer the most immediate advances in weapon systems capabilities; and those in Group C, principally emerging technologies whose applications are farthest in the future and most difficult to identify in detail at this time.

Table 3. Critical Technologies in Three Priority Groups (Technologies are listed in alphabetical order within each group)

GROUP A:

- Composite Materials
- Computational Fluid Dynamics
- Data Fusion
- Passive Sensors
- Photonics
- Semiconductor Materials and Microelectronic Circuits
- Signal Processing
- Software Producibility

GROUP B:

- Air-Breathing Propulsion
- Machine Intelligence and Robotics
- Parallel Computer Architectures
- Sensitive Radars
- Signature Control
- Simulation and Modeling
- Weapon System Environment

GROUP C:

- Biotechnology Materials and Processes
- High-Energy Density Materials
- Hypervelocity Projectiles
- Pulsed Power
- Superconductivity

In planning a balanced S&T program for submission to Congress, both priorities and budget constraints must be taken into account. The need for balance in the S&T program was discussed more fully in last year's Critical Technologies Plan. Any redistribution of funding into the critical technologies that would come at the expense of the rest of the S&T program could unbalance the overall S&T effort.

D. INDUSTRIAL ASSESSMENTS

Relevant manufacturing technologies are treated under each critical technology heading. Table 4 summarizes the product/process orientation of the critical technologies. Note that "process" may refer to materials processing (as in semiconductors, superconductivity, or biotechnology), or it may refer to the development of tools for process control or analysis (as in robotics or simulation and modeling).

Table 4. Product/Process Orientation of the Critical Technologies

	Primarily Product Development	Mixed Product and Process Development	Primarily Process Development
1. Semiconductor Materials and Microelectronic Circuits			X
2. Software Producibility		X	
3. Parallel Computer Architectures		X	
4. Machine Intelligence and Robotics		X	
5. Simulation and Modeling		X	
6. Photonics		X	
7. Sensitive Radars	X		
8. Passive Sensors		X	
9. Signal Processing		X	
10. Signature Control		X	
11. Weapon System Environment	X		
12. Data Fusion	X		
13. Computational Fluid Dynamics		X	
14. Air-Breathing Propulsion		X	
15. Pulsed Power	X		
16. Hypervelocity Projectiles	X		
17. High Energy Density Materials		X	
18. Composite Materials			X
19. Superconductivity		X	
20. Biotechnology Materials and Processes			X

1. Related Industry Activities

The Department of Defense and the Department of Energy have a special and strong interest in, as well as considerable influence on, all related science and technology activities. Hence their S&T planning cannot be done in isolation. During the preparation of the Critical Technologies Plan, several interactions with industry took place.

The Aerospace Industries Association (AIA) sponsors a National Center for Advanced Technologies (NCAT) to coordinate and integrate plans for 10 key technologies: composite materials, advanced sensors, rocket propulsion, air-breathing propulsion, superconductivity, software development, optical information processing, artificial intelligence, computational science, ultrareliable electronics systems. NCAT has assembled industry teams in all these technologies and is publishing a series of reports.

Three industrial associations, the Aerospace Industries Association (AIA), the Electronic Industries Association (EIA), and the National Security Industrial Association (NSIA) surveyed their members on the 22 technologies in last year's Critical Technologies Plan. The results indicate a large measure of agreement with the DoD assessments; details are contained in the associations' final report (January 1990).

2. Independent Research and Development in US Industry

Company-sponsored R&D data is proprietary. The DoD and NASA sponsor an independent research and development (IR&D) program in industry, and major participating companies provide proprietary data to the government. Industry expenditures amount to approximately $7 billion/year, of which about $3.5 billion is reimbursed by the government through allowable overhead charges. The IR&D program represents approximately 8 percent of the R&D sponsored by the private sector. While this figure is only a relatively small proportion of industrial R&D, it is significant enough to indicate trends among large defense and aerospace contractors. (Thus, it may yield significant data in the aerospace and defense sector, but is probably of little use for information on biotechnology trends, where much of the work is done by small, non-defense oriented companies.)

The major portion of IR&D is devoted to development efforts. With that caveat, trends can be identified. An analysis was made of IR&D funding distribution among the 22 critical technologies on last year's list and compared with the funding distribution of

DoD-sponsored R&D reported in last year's Critical Technologies Plan. Technologies receiving proportionately higher funding in IR&D than in contracted R&D are:

- Fiber optics
- Simulation and modeling
- Air-breathing propulsion (turbines)
- Composite materials.

Among the technologies receiving proportionately lower funding under IR&D, are (ending with the lowest):

- Photonics
- Biotechnology
- Superconductivity
- High power microwaves.

The first four technologies listed have near-term, commercial applications in common; for instance, fiber optics in communication networks or turbines in commercial aircraft. The second group of four critical technologies have few near-term applications. Three are still largely in basic research, and one (high power microwaves) has mainly military applications. By default, DoD becomes the key player in sponsoring the development of the latter technologies for defense applications.

E. INTERNATIONAL TECHNOLOGY AND INDUSTRIAL BASE

Recent political changes in Eastern Europe and elsewhere may affect technology transfer and our entire industrial base posture. Each of the technology areas is presented in Appendix A, along with some preliminary thoughts regarding how global trends in defense critical technologies may affect the US industrial base.

1. Highlights in International Capabilities

A summary assessment of foreign technological capabilities in the 20 critical technologies relative to the United States is shown in Table 5. Reflecting recent international developments, Table 5 addresses the Soviet Union and Eastern European countries separately.

Table 5. Summary of Foreign Technological Capabilities

Critical Technologies	USSR	NATO Allies	Japan	Others
1. Semiconductor Materials and Microelectronic Circuits	▨	□□	□□□□	□□ Israel
2. Software Producibility	▨	□□	□□	□□ Various Countries
3. Parallel Computer Architectures	▨	□□	□□	□□ Switzerland, Israel, Hungary
4. Machine Intelligence and Robotics	▨	□□□	□□□□	□□ Finland, Israel, Sweden
5. Simulation and Modeling	▨	□□□	□□□	
6. Photonics	▨▨	□□	□□□□	□ Various Countries
7. Sensitive Radars	▨	□□	□□	□□ Sweden
8. Passive Sensors	▨▨	□□	□□	
9. Signal Processing	▨▨	□□	□□	□□ Sweden, Israel
10. Signature Control	▨▨	□□	□□	
11. Weapon System Environment	▨▨▨	□□□	□□	□ Various Countries
12. Data Fusion	▨▨	□□	□□	□□ Israel
13. Computational Fluid Dynamics	▨	□□	□□	□□ Sweden, Israel □ India, China, Australia
14. Air-Breathing Propulsion	▨▨	□□□	□□	
15. Pulsed Power	▨▨▨▨	□□	□□	□ Various Countries
16. Hypervelocity Projectiles	▨▨▨	□□	□□	
17. High Energy Density Materials	▨▨▨	□□□	□□□	
18. Composite Materials	▨▨	□□□	□□□	□□□ Israel
19. Superconductivity	▨▨	□□	□□□□	□□□ Switzerland
20. Biotechnology Materials and Processes	▨▨	□□□	□□□□	□□ Various Countries

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to make any immediate contribution

2. Exchange Agreements

Formal DoD agreements represent only a fraction of all international technology cooperation. Civilian government agency, academic, and industry exchanges and joint efforts all contribute significantly to an increasingly complex global technology infrastructure. Nevertheless, these formal agreements form the basic framework within which militarily important exchanges occur.

Agreements surveyed fall into several categories:

- Exchanges with NATO allies. These are broadly based studies and scientific exchanges with a focus toward long-term scientific advances.
- Exchanges under The Technical Cooperation Program (TTCP) among the United States, Canada, United Kingdom, Australia, and New Zealand. These cover approximately 100 topics.
- Country- and technology/system-specific agreements. These number in the hundreds and cover a wide spectrum of exchanges, ranging from basic research topics to information for production and operation of existing US systems.

Specific examples are given in each technology section in Appendix A.

F. PLANNING FOR THE FUTURE OF SCIENCE AND TECHNOLOGY

The DoD S&T planning process, of which the Critical Technologies Plan is a part, may be divided into three stages.

- *Stage 1* consists of the development of a strategic plan for the entire science and technology program, the DoD S&T Investment Strategy.
- *Stage 2* begins with the formation and selection of the critical technologies and includes the development of a brief but comprehensive status report on each technology, the Critical Technologies Plan.
- *Stage 3* will lead to a series of implementation plans, one for each critical technology. The task of developing these plans has been assigned to lead organizations within DoD and DoE.

These three stages together constitute an overall planning process, of which the Critical Technologies Plan is an integral part.

Appendix A

ANALYSES OF CRITICAL TECHNOLOGIES

INDEX OF CRITICAL TECHNOLOGIES

ORGANIZATION OF EACH CRITICAL TECHNOLOGY SECTION

Each of the following 20 critical technology chapters is organized under the following headings.

A. DESCRIPTION OF TECHNOLOGY

B. PAYOFF
   1. Impact on Future Weapon Systems
   2. Potential Benefits to Industrial Base

C. S&T PROGRAMS
   1. Milestones
   2. Developing the Technology
   3. Utilizing the Technology

D. RELATED MANUFACTURING CAPABILITIES
   1. Current Manufacturing Capabilities
   2. Projected Manufacturing Capabilities

E. RELATED R&D IN THE UNITED STATES
   1. R&D in Other Agencies
   2. R&D in the Private Sector

F. INTERNATIONAL ASSESSMENTS
   1. Technology Base and Industrial Base
   2. Exchange Agreements

1. SEMICONDUCTOR MATERIALS AND MICROELECTRONIC CIRCUITS

A. DESCRIPTION OF TECHNOLOGY

Since its inception three decades ago, microcircuit technology has been responsible for the creation of dozens of new industries such as data processing, home computers, robotics, software, and video games. It has fundamentally altered communications, education, health care, recreation, entertainment, and work activity. For the soldier in the field, it has extended the range at which his eyes can see and his ears can hear. It has expanded the ability of his brain to make decisions on a wide variety of complex information and multiplied the muscle power he can deliver against an enemy. Because microcircuit technology has affected a wide range of diverse industries and capabilities, it is considered critical to the future of our national economy and our national security.

The importance of microelectronics devices derives from the ability to shrink the minimum features of basic circuit elements such as the transistor. Shrinking feature size results in the ability to achieve greater circuit densities (circuit elements per area). During the past two decades, this technology has doubled the storage capacity of dynamic random access memories every 2.5 to 3 years. Other important benefits achieved with shrinking size include lower power demand, higher reliability, lower cost, and very high speed.

While microelectronics technology makes things smaller, they do not necessarily become simpler. The fabrication of these devices is probably the most complex manufacturing task man has ever attempted. It requires extremely high quality semiconductor materials and sophisticated equipment that can make patterns that are smaller than the wavelength of visible light. It requires dimensioning gate lengths that are smaller than a millionth of a meter and measuring the thickness of surface coatings in molecular diameters. A typical microcircuit will require approximately 400 separate manufacturing steps, each of which must achieve a near perfect reliability to allow a cost-effective yield of the final device. These sensitive devices, essentially made of glass (silicon dioxide), must be packaged so that they can withstand rugged military environments and be able to tolerate high levels of radiation.

This area includes the investigation and characterization of a variety of new semiconductor materials that offer the potential for significant increase in performance and cost. It encompasses the development of new manufacturing methods and tools to produce quality wafers from which circuits can be built. This area is also concerned with developing a wide range of technologies that are necessary to produce highly advanced microelectronic circuits. These technologies include

- Aggressive computer-aided design (CAD) techniques that will allow designers to creatively manipulate constantly increasing amounts of complex circuitry, extend current practice into the system-to-chip design concept, and significantly reduce the design time

- Far-term, high-risk lithography technologies such as electron beam (E-beam), x-ray, and ion beam
- Fabrication technologies that capitalize on industry practices but focus on military needs such as low-volume manufacturing, radiation hardening, and extended temperature range devices
- Packaging and interconnect technologies that enhance circuit performance and prevent degradation
- Technologies that improve the overall quality control of microelectronic circuits.

For purposes of description, the components of microelectronics fabrication may be divided into wafer preparation technologies (the technologies, equipment, and processes used for mass production of quality semiconductor wafers, including crystal growers, slicers, polishers, and preliminary dopant equipment); wafer fabrication technologies (the body of processing technologies used to fabricate integrated circuits on prepared wafers); mask making and design technology; and packaging, assembly, and test technologies.

Future development of semiconductor technology involves numerous technology challenges. A representative list of current challenges includes creation of low-volume production techniques for devices having a minimum feature size of less than two-tenths of a micrometer (micron); improved radiation hardening techniques; improved CAD tools; better packaging, assembly, and testing of these complex circuits; and improved compound semiconductor materials preparation (see the table that follows).

Critical Technology Challenges in Semiconductor Materials and Microelectronic Circuits

• Low-volume production techniques for sub 0.2 micron devices
• Radiation hardening
• CAD for complex circuits
• Sub 0.3 micron mass production lithography
• Packaging/interconnect
• Compound semiconductor materials preparation

Silicon-based semiconductor technology is highly advanced and continues to comprise the bulk of conventional integrated circuitry and high-power devices. The dominance of silicon-based semiconductor manufacturing technology will continue for a decade or more. Thus, long-term DoD/DoE efforts in microelectronics technology can be expected to significantly involve silicon technologies for the indefinite future. In fact, advances in silicon-based technology continue at an impressive rate, making it progressively more difficult for alternative technologies to compete with it over the near- to mid-term.

Digital gallium arsenide (GaAs) technology is expected to become competitive with silicon-based microelectronics in the long term and promises significant advantages over comparable silicon-based devices, especially for military applications. For example, GaAs has an electron drift velocity nearly seven times faster than silicon and inherently better resistance to radiation damage than does silicon. Thus, a GaAs integrated circuit may eventually be many times faster than a silicon-based counterpart of similar design and complexity. Also, unlike silicon, gallium arsenide has a direct bandgap, thus providing it with wider potential applications than silicon possesses (e.g., in optoelectronic devices). Gallium arsenide and other compound semiconductors (such as indium phosphide, indium antimonide, and mercury-cadmium-telluride) continue to play important roles in microwave and millimeter wave circuit devices as well as roles in other wave bands (e.g., infrared and optical). Despite its recent advances, GaAs integrated circuit fabrication technology remains relatively undeveloped when compared with silicon technology, which has benefitted from more than two decades of research and development.

B. PAYOFF

1. Impact on Future Weapon Systems

Microelectronics technology meets each of the six major criteria used for selecting the critical technologies. Microelectronics technology experiences major performance improvements at the component level (such as order of magnitude improvements in speed and circuit complexity) every three to five years, resulting in significantly improved military system and subsystem performance and capabilities. Furthermore, micro-miniaturization technology has proven to dramatically increase the reliability, dependability, and availability of electronic components by reducing their physical size and power requirements, while also providing massive economies of scale for cost-effective production of large quantities of devices. Furthermore, microelectronics technology has a pervasive effect on virtually every US weapon system, current or future. For example, increasing miniaturization techniques allow major modifications of current weapons platforms (such as the creation of aerodynamically unstable aircraft controlled by onboard microprocessors, as on the F-16) to the development of radically new weapons concepts (e.g., "brilliant" weapons). The ability to build in self-test circuitry will greatly reduce maintenance problems and improve overall systems reliability. Also, microelectronics technology may critically affect operations scenarios and deployment tactics by providing ever increasing decision aids and communications capabilities between tactical/theater commanders and their assets. Increasing circuit complexity and functionality also will allow major expansion of key military operational capabilities for reconnaissance, surveillance, and target acquisition (RSTA), command, control and communications (C^3), and battlefield lethality. For example, the availability of gigabit (10^9 bits) dynamic random access memory (DRAM) envisioned by 1995 will increase information access to large data bases by three orders of magnitude.

Silicon technology will continue to prevail during the very high-speed integrated circuit (VHSIC) era and for a long time thereafter and will continue to be the technology of choice for specialized applications (such as high-power solid-state switches in hypervelocity and beam weaponry). At the same time, GaAs will remain the most readily available and commonly used material for microwave and millimeter-wave frequency devices and circuits. These circuits are critical building blocks for DoD electronic warfare, radar, smart weapons, and communications systems. The high performance, potentially low cost, unit-to-unit reproducibility, and inherent radiation hardness of GaAs circuitry make it essential for performance of front-end functions in these systems. GaAs is also in solid-state active aperture antennas (phased arrays). In the 1990s, the same integrated circuit elements will appear more frequently in equipment for communications, electronic warfare, electronic intelligence, avionics, missile guidance and control, and surveillance from space.

Important as microelectronics circuits are today, future weapons systems will rely even more upon advances in semiconductor fabrication techniques. In addition, the ability to design and integrate new microelectronic components into weapons systems is an essential corollary to the device fabrication technology. The success of our future defense posture relies in part on our ability to rapidly exploit advances in microfabrication technology at the systems level.

2. Potential Benefits to Industrial Base

Most of the R&D incident to the military-oriented semiconductor technology thrust is directly applicable to the domestic industrial front. Exceptions include DoD requirements for level of radiation hardness, degree of ruggedness, and perhaps higher frequency millimeter-wave capability. The thrusts toward ultra levels of miniaturization and higher speed of operation are clearly applicable across a broad front of domestic electronics technology and will continue to benefit many phases of industry and the consumer. The recently completed VHSIC program is one example; it has directly affected the US industrial base in this regard. Direct, immediate beneficiaries of the VHSIC program have included the computer, automotive, telecommunications, and robotics industries. It would be difficult, however, to identify any domestic segment that would not be affected, directly or indirectly, by advances in semiconductor technology, whether based upon silicon or gallium arsenide. Sematech, the semiconductor manufacturing technology consortium of US industrial firms and the DoD, has potential to contribute to the US technology base and competitiveness in the worldwide semiconductor industry. Sematech is directed toward making the United States a world leader in future submicron silicon technology. A major thrust of Sematech includes the development and enhancement of the semiconductor equipment industry and materials supply base.

DoD efforts in GaAs technology will also affect industrial development of future microelectronic materials and devices. High-speed GaAs circuits and specialty infrared sensors are beginning to find commercial markets. High-speed GaAs processors are being used in next-generation supercomputers. Discrete high electron mobility transistors are also being used in television receivers. GaAs, aluminum gallium arsenide (Al Ga As), and strained-layer (Ga,In)As transistors are being used in this area. Long-wavelength lasers (constructed from epitaxial layers grown either strained or lattice matched to InP) will soon significantly impact communications. High-performance detectors for these longer wavelength systems are available. Optical interconnects for integrated circuits can provide very high-volume, high-speed chip-to-chip communication for a variety of computing and data storage applications.

C. S&T PROGRAMS

1. Milestones

The following table summarizes the DoD planned technical milestones to the year 2005, in the area of microelectronic materials, circuits, and their fabrication.

Milestones--Semiconductor Materials and Microelectronic Circuits

Technical Area	By 1995	By 2000	By 2005
VHSIC electronic circuits providing highly reliable and radiation-hardened technology	• 0.5 micron low-volume production available in digital silicon devices	• 0.2 micron low-volume production of digital silicon devices	• Less than 0.1 micron production of low-volume digital silicon devices
MIMIC electronic circuits providing reliable analog capabilities for system front-ends	• Continuous increases in single function (amplifiers, oscillators, mixers, switches) chips available in 1 to 20 GHz range	• Integrated multiple function chips available over entire 1 to 100 GHz range • CAD/production facilities available to meet large range of system requirements • Heterojunction MIMIC	• Microwave/digital integrated circuits • Microwave/optical integrated circuits
Commercial Sematech silicon circuits	• 0.8 micron production capability (high volume) • 35 micron (low volume)	• 0.35 micron production capability (high volume)	
Design	• Continued test/reliability/process design on advanced parallel computers • Fast prototyping of continued circuits	• Testable, complex designs generated by scalable design tools • Rapid prototyping to second-level packaging	• Fail-safe, fault-tolerant self-repairing adaptivity inherent in microelectronic subsystems
Manufacturing	• Expanded qualification procedures for gate array microcircuits	• National quality procedures for microelectronics available	• Wafer scale integration for high-volume production
Fabrication of compound semiconductors	• ASICs • Mass production of 4-inch diameter 25 kg boules for GaAs substrates • Continued progress on improvement of MOMBE and MOCVD single wafer deposition equipment	• Production of 5-inch diameter GaAs substrates • Equipment available for simultaneous expitaxial growth on multiple wafers of GaAs	• Development of reliable sources of InP wafers • Production of 6-inch diameter 50 kg boules for GaAs substrates
III-V integrated circuits (e.g. GaAs)	• Complementary logic • Medium-scale integration gate arrays	• Large-scale integration complementary logic circuits in production	• III-V integrated circuits fully compatible with silicon-based circuits

2. Developing the Technology

Electron device R&D addresses DoD performance requirements that are often quite generic, and DoD programs in turn are influenced strongly by the materials structures that are realizable as well as by available device processing technology. By the year 2000, the following technologies and capabilities should be ready for incorporation into production development programs:

- Gigahertz speed signal processing microelectronics components
- Giga-sample rate analog-to-digital converter technology
- Subquarter-micrometer feature sizes
- Wafer-scale integration of logic and memory devices
- Multilevel (3-D) integrated circuits
- Gigahertz speed GaAs and other compound integrated circuits.

To achieve these results, DoD has employed a number of microcircuit technology development efforts. Perhaps best known is the DoD VHSIC program. Now completed, the VHSIC program focused upon refining the technologies required to achieve integrated results with submicron (0.5 micron) feature sizes. This refinement allows fabrication of extremely dense and high-speed integrated circuits. In addition to the VHSIC program, the Semiconductor Manufacturing Technology (Sematech) consortium is focusing on advanced manufacturing processes technology and equipment development for next-generation circuits. It is emphasizing strengthening the domestic companies that make the equipment used to fabricate microelectronic circuits and improving the reliability and utilization of the equipment. Sematech's specific program is still undergoing evolution. DoD is also pursuing advanced lithography technology (ultra-violet, x-ray, ion beam, and electron beam) and is developing radiation-hardened semiconductor devices (for both metal-oxide semiconductor and bipolar device types). DoD is also considering tri-Service initiatives in microcircuit packaging and CAD.

DoD's and DoE's engineering of semiconductor materials focuses on interface formation, growth of 3-D structures, and defect characterization and engineering. The goal of the research is to fully realize the materials-by-design concept where new and unique materials are constructed on the atomic scale with application-specific properties. The thrust area includes research on understanding the thermodynamic and kinetic principles that control the evolution of interfacial chemistries and microstructures during growth of overlayers; studying the etching and regrowth of semiconductor materials to form increasingly complex 3-D structures; and developing insight and methodologies for the beneficial utilization and manipulation of defects to tailor the properties of a semiconducting material.

A summary of total S&T funding[1] is shown in the table below.

Funding--Semiconductor Materials and Microelectronic Circuits ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
2,100	450	460	480	480	480	480

3. Utilizing the Technology

Silicon-based digital and analog integrated circuits are widely used throughout DoD weapon systems and communication platforms. In fact, an important objective of the DoD VHSIC program was to speed the utilization of the products created by advanced semiconductor production technology by providing for more rapid component insertion rates. This pervasive use of silicon-based integrated circuits will continue for the indefinite future.

DoD's microwave and millimeter-wave monolithic integrated circuit program (MIMIC) is focused on the development and production of affordable, reliable analog circuits for use as sensors and signal processors in the front-ends of electronic warfare, radar, smart munitions, and communication systems. These circuits, fabricated primarily from gallium arsenide, operate at frequencies from 1 to 100 GHz. Devices being used include GaAs metal-semiconductor field effect transistors (MESFETs), high electron mobility transistors (HEMTs), and heterojunction bipolar transistors (HBTs). Other programs develop millimeter-wave power devices, wafer-scale technology, molecular beam epitaxy, and superlattice technology.

Rapid insertion of electronic technology into weapons systems is needed to ensure continued defense system superiority. Technology options to fulfill this need primarily involve new and more encompassing CAD techniques. In this regard, the VHSIC hardware description language (VHDL) used in the design, specification, simulation, and test of microcircuits has been adopted as an international standard. The VHDL design concepts are being expanded beyond the chip level and will encompass system level requirements. This is expected to greatly affect the timely utilization of microcircuit technology.

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1 Funding is derived from programs in the DoD and DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

Microcircuit technology currently is dominated by silicon-based manufacturing processes. Manufacturers often utilize silicon in microcircuits whose minimum feature size is 0.7 microns and less. These microcircuits are fabricated from boules of silicon grown to as large as six inches in diameter. A large percentage of microcircuits in current weapon systems applications are customized parts, called application specific integrated circuits (ASICs). DoD and commercial manufacturing requirements in silicon are very similar, though not completely identical. Existing manufacturing issues in silicon include competing lithography processes and packaging and CAD for high-density circuits.

GaAs technology is rapidly expanding and in the next decade may make significant in-roads in the analog IC market. At least 27 US companies have GaAs programs. The DoD has made a significant GaAs investment through the $225 million MIMIC program. The primary objective of the program is to reduce the cost of monolithic microwave integrated circuits, and it addresses critical areas such as CAD, assembly, and test. The cost of MIMIC chips has been reduced from 20 dollars per mm^2 to 4 to 8 dollars. Eighty MIMIC chip designs have been completed and half of these have been fabricated with yields as high as 93 percent. Progress is also being made in digital GaAs manufacturing. Three pilot production lines have achieved record quality levels for digital GaAs, and a variety of technology insertions are underway.

2. Projected Manufacturing Capabilities

While significant progress in GaAs raw material has been made, challenges remain to achieve high-volume, low-cost manufacturing. One challenge is the uniformity of the epitaxial growth layer (which is critical to device performance and yield). DoD has initiated a manufacturing technology program to develop the technology for a 6-inch, 20 kg boule. Inherent in this program is the effort to control the growth of the boule to produce a more uniform wafer. Techniques such as metal-organic chemical vapor deposition (MOCVD), metal-organic molecular beam epitaxy (MOMBE), and molecular beam epitaxy (MBE) are being developed and refined. While the MBE technique provides good control, it is a slow process. To improve throughput, techniques and equipment are needed to provide for simultaneous epitaxial growth on multiple wafers. Development of non-destructive evaluation (NDE) techniques are also required to support high-volume production. These techniques, such as on-wafer characterization of circuits, are essential to provide real-time data for automated statistical process control. Many of these advancements also will apply to silicon. Other contemporary DoD manufacturing technology investments supporting and utilizing this critical technology include improving the yield of semiconductor materials for high-performance seekers and sensors used by missiles and target acquisition systems; automating hybrid circuit production; establishing processes to produce replacement integrated circuits that are no longer in production but are still being used in DoD weapons systems; and working toward a flexible microelectronics manufacturing system.

Milestones--Industrial Base (Manufacturing Capabilities)

	By 1995	By 2000	By 2005
Material	• Wafer quality (GaAs)	• SOI wafer (Si)	• Enhanced rad hard • Processing IC MOMBE
Fabrication and assembly	• Circuit emulation (Si)	• Cluster tool processes • Automation • X-ray lithography • Multichip packaging	• 3-D circuits • Integrated cluster tool processing • Data driven/integrated manufacturing
Test and inspection	• Multi-dimensional x-ray inspection • Holographic inspection	• Z-plane inspection on wafer testing • Electro-reflective inspection	• Sensor-based manufacturing

A large portion of company independent research and development (IR&D) funding is spent in the microelectronic area, but with the rapid technology development and increasing complexity and sophistication of semiconductors, it is increasingly difficult for a company to fund the efforts to implement all of these advances. To help maintain a robust US industrial base in this critical technology, industry, government, and academia have established cooperative efforts such as Sematech. Semiconductor production equipment is very expensive and may be obsolete in a few years. DoD microelectronics manufacturing S&T efforts include developing a flexible microelectronics manufacturing system for application-specific ICs having in-situ sensors, expert system process control, and single-wafer processing. This process is a step toward a totally data-driven, integrated manufacturing capability in the semiconductor industry.

E. RELATED R&D IN THE UNITED STATES

US research work involves all major facets of the technology, with special emphasis on cost-reduction bottlenecks (such as clean-room practices and equipment and high-throughput lithography), and new miniaturization techniques (such as 3-D scaling processes).

The bulk of this research is applied to development of commercially used microcircuits. While much commercial R&D has direct military input, and vice versa, only about 7 percent of the semiconductor market in recent years has been related to military sales. As a result, issues of importance to DoD fabrication technology (such as radiation hardening) usually are not emphasized heavily in the commercial technology.

1. R&D in Other Agencies

The Department of Energy has a research program in the fabrication of epitaxial thin films and development of new devices in semiconductor materials. The program encompasses all phases necessary for the realization of new devices, from epitaxial film growth through device design (and fabrication) to testing. Devices under development include ICs and opto-electronic devices. This work includes a strong effort in strained layer materials systems to determine their advantages in modern devices, i.e., lasers, transistors, and detectors. The materials growth and device research and development program is supported by substantial theoretical work, experimental materials studies including growth and characterization, and development of in-situ diagnostic techniques. The National Science Foundation (NSF) and the National Institute of Science and Technology (NIST) also conduct semiconductor materials and microelectronic circuit research. The NSF provides strong linkages between universities, industry, and government.

2. R&D in the Private Sector

The US private sector continues to contribute significant levels of R&D in silicon-based technology development. Private industry R&D investment rates can be as high as 25 percent or more of company sales. The level of US R&D in GaAs preparation technology is increasing as the technology becomes a stronger competitor to existing silicon-based microelectronics. Currently, GaAs R&D investment is not nearly as extensive as is existing silicon-based R&D, but most major US semiconductor firms have efforts underway.

F. INTERNATIONAL ASSESSMENTS

1. Technology Base and Industrial Base

The US industry dominated the worldwide semiconductor market since the late 1960s. Its leadership, however, has suffered a constant erosion by industrialized countries (primarily Japan). In 1986, the US lost world market share leadership. Future trends indicate continued market share declines. Closely coupled with this market share decline is the decline of the semiconductor materials and equipment industry that supports semiconductor manufacturers. These problems are being addressed by the joint industry/DoD Sematech program.

While the United States has lost its world manufacturing leadership position, it is still generally recognized as the world technology leader. However, since manufacturing, and ultimately sales, generates the revenue for R&D, the future of US technology leadership also is somewhat questionable. The implications of the decline in technology and manufacturing leadership for the DoD include the potential for foreign dependence in the critical area and increase the possibility that advanced microcircuit technology may be made available to our potential adversaries.

Still, the US microelectronics industry today leads the USSR in semiconductor and microelectronic R&D in virtually every area of significance. The USSR remains limited in its ability to close the microelectronic technology gap due to a variety of processing difficulties and systemic problems.

Among the east European countries, East Germany is believed to have the most significant IC fabrication capabilities. These capabilities are likely to be greatly enhanced by increased access to western technical expertise.

Soviet work in GaAs microelectronics has been a longstanding adjunct to their microwave device R&D. While their ability to produce high-quality GaAs is significant, they are believed to lag substantially in their ability to apply the material to devices in volume production.

The table on the following page provides a summary comparison of the United States and other nations for selected key aspects of the technology. Ongoing international R&D indicates potential international capabilities to contribute to meeting the challenges and goals identified:

- VLSI/VHSIC <0.3 micron feature size
- Implementation of Bi-CMOS and GaAs MIMIC circuits
- Bulk or epitaxial growth of compound semiconductor materials
- Radiation hardening.

Japan is believed to be ahead of US efforts in GaAs integrated circuit fabrication techniques. Japan's capabilities in GaAs materials and circuit fabrication could make significant contributions to US capabilities and the needs of the Western alliance.

In terms of VHSIC-related fabrication at very large scale integration (VLSI) levels, Japan now dominates in memory device manufacture, and in most aspects of microelectronics manufacturing, with the exception of ASICs. The existence of 0.5 micron VHSIC pilot production lines in the US represents a world leadership position. It is expected that the Japanese will surpass this capability within the next few years.

The US maintains a worldwide lead in microprocessors, but the Japanese are making a dedicated effort to narrow the gap. They are pursuing an original approach, which, if successful, will provide a high degree of compatibility with existing US chips, while offering a more open architecture designed to support a real-time distributed processing operating system. Indicative of Japanese advances is the announcement of a 64-bit microprocessor chip with basic features similar to US products.

Our NATO allies, individually, do not presently rival either the United States or Japan. This situation could, however, drastically change in the near term. The European countries have extensive capabilities in a number of important niche technologies. The formation of such joint efforts as the European Strategic Program for Research in Information Technology (ESPRIT) and the Joint European Submicron Silicon program (JESSI), coupled with the planned economic unification of Europe in 1992, can only be expected to enhance the integration and effectiveness of these existing capabilities.

The ESPRIT program is active in the area of Bi-CMOS, and the UK and FRG have developed some significant capabilities in the area of GaAs. These NATO countries are also actively pursuing other advances in silicon-based technologies. JESSI (present participants include companies from the FRG, the Netherlands, and Italy) hopes to extend the consortium's capability in design systems, materials, and fabrication to the 4 millon bit DRAM level. With regard to certain underlying niche technologies, these activities have considerable potential for cooperation. In terms of the supporting technologies for fabrication of VLSI/VHSICs, Britain's Science and Engineering Research Council has announced important advances in E-beam technology that possess significant potential for submicron lithography.

Summary Comparison--Semiconductor Materials and Microelectronic Circuits

Selected Examples	USSR	NATO Allies	Japan	Others
VLSI/VHSIC <0.3 micron features size	▨	□□	□□□□	
Implementation of Bi-CMOS and GaAs MMIC circuits	▨	□□[b]	□□□□	□□ Israel
Bulk or epitaxial growth of compound semiconductor materials	▨▨[b]	□□□[b]	□□□□	□□ Israel
Radiation hardening	▨▨[b]	□□[a]	□□□[a]	
Overall[c]	▨	□□	□□□□	□□ Israel

[a] Basic contribution from circuit design/fabrication advances and in GaAs materials.
[b] Limited quantity high-quality GaAs materials.
[c] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

Within NATO, a large number of companies have active research programs in GaAs and indium phosphide (InP). The UK is reported to have developed a unique design architecture for GaAs digital filters. France appears to be the front runner in promoting and using GaAs devices, and several other NATO countries are reported to have active programs including FRG, the Netherlands, and the UK.

Canada has an active program in CAD and basic material research. Canada is reported to have developed a CAD program that characterizes parasitic effects, which are of particular interest in the development of higher density MIMIC devices.

The following countries possess capabilities only slightly behind, equal to, or slightly ahead of the best US capabilities and could contribute to meeting future US technology challenges.

- UK: Strong in crystal growth, E-beam lithography, and E-beam diagnostic equipment. Also of interest is the report that a major US firm (IBM) has entered into a contract with a UK firm to purchase compact synchrotrons for its x-ray lithography.
- FRG: Strong in silicon crystal growth technology, metallization equipment, x-ray lithography. The FRG is also reported to be pioneering the use of differential molecular-beam epitaxy for the fabrication of stacked ICs.
- Netherlands: Strong in chemical-vapor deposition (CVD) and E-beam lithography.
- Switzerland: Strong in wire and die bonders, mask blanks, and thin-film deposition.
- Israel: Strong in CAD and aspects of compound semiconductor materials processing.

In addition, South Korea is making significant progress and is reported to have the capability to produce VLSI devices with 1.25 micron or finer feature sizes. While South Korea appears, for the present, to be drawing on US and Japanese technology, it has the resources and the potential to pursue innovative efforts in the near future. The same appears to be true, but perhaps to a slightly lesser degree, of Taiwan and Hong Kong.

Of interest is the number of European researchers who believe that GaAs will not prove to be the last word in high-speed semiconductor materials. Specifically, InP is believed to offer higher radiation resistance, with higher purity (99.99999 percent claimed) and better fabrication repeatability than GaAs. This approach is being actively pursued by France and several German firms. Also indicative of significant capability in this technology is a French effort in complex GaAs/GaA/As and InGaAs/P structures for integrated optics. Israel also is believed to be making progress in processing of compound semiconductor materials.

2. Exchange Agreements

There is a high level of exchange activity in the area of microelectronics between the United States and free world countries. US participation in NATO programs in physics and electronics and optical and infrared technologies provide a mechanism for exchanges of fundamental scientific information in underlying technologies of semiconductor materials and devices.

The Technology Cooperation Program (TTCP) provides a vehicle for a range of applicable exchange activities in basic semiconductor materials, microelectronic devices, and electro-optic materials and devices.

Each of the Services also have exchanges with NATO and other friendly nations in areas of specific interest. These exchanges provide a mechanism for technology sharing in a wide spectrum of materials and device fabrication technologies, including electro-optics and millimeter wave and microwave technologies applicable to processing of compound semiconductor materials and MIMIC fabrication. Examples of Service programs illustrating the breadth of activity include programs in microelectronics and their applications with France and Germany and programs in electro-optics and infrared technology relevant to compound semiconductor materials and devices with France, Germany, Italy, Spain, and some non-NATO nations.

2. SOFTWARE PRODUCIBILITY

A. DESCRIPTION OF TECHNOLOGY

Software has become the focus of functionality and flexibility in most large-scale military and commercial systems.

Critical Technology Challenges in Software Producibility

- Reusable software
- Automatic software generation
- Secure and trusted software
- Software for parallel and heterogeneous distributed systems
- Software and system engineering environments
- Real-time/fault-tolerant software

The major areas of research in software technology cover a range of important technology challenges for defense software. Reusable software encompasses the software components (e.g., designs, system architectures, requirements, documentation, concepts, and source and object code) that are developed for use in multiple systems. This technology area addresses reusable software design, development, cataloging, storage, retrieval, and integration into systems. Automatic software generation is the automation of today's labor-intensive software development and support activities. Secure and trusted software is software that prevents malicious entry into government software, protects the integrity of classified material and data, and guarantees a level of assurance that the software will operate correctly and safely. Software for parallel and heterogeneous distributed systems exploits the capabilities of large-scale parallel and heterogeneous distributed hardware architectures ranging from multi-processor embedded systems to heterogeneous networks of workstations.

Software and system engineering environments are collections of software tools and associated hardware integrated within some framework that are utilized to develop and support systems throughout their life cycles. Real-time/fault-tolerant software is software that must satisfy complex timing properties, such as response deadlines, while interacting with external environmental phenomena (such as motion, temperature, pressure, and physical position). Predictable behavior is crucial, since failure to satisfy timing constraints may result in immediate catastrophic events, with little or no opportunity for human intervention.

B. PAYOFF

1. Impact on Future Weapon Systems

Software is a key element of virtually all major defense systems. Software development and maintenance costs in DoD are estimated to be as much as 10 percent of the entire DoD budget, with rework, evolution, and maintenance accounting for more than 80 percent of these costs. Because of the critical role that software plays in system functionality, deficiencies in software affect overall system performance out of proportion to the software development and maintenance costs.

The increasing allocation of system functions to software instead of hardware offers the important advantages of reduced system replication cost as well as the flexibility to adapt to changing system requirements. However, it has caused an increase in the number of lines of code, with concomitant growth in software complexcity and cost, resulting in an immediate need for technologies to manage the burgeoning inventory of defense software through increased automation.

Reusable software is a key to solving the increasing-cost-versus-declining-budget dilemma. Reuse leverages the best solutions for use in defense systems. However, many issues, both technical and managerial, must be solved before reuse can become widely implemented. Disincentives for reuse must be replaced with economic incentives. Software repositories must be developed based on domain analyses that support the creation, validation, cataloging, extraction, maintenance, and evolution of reusable software.

Automatic software generation also provides considerable leverage in a declining budget environment. Today, software development and support are labor-intensive, costly activities. Automation techniques and knowledge-based software tools that have been demonstrated on a small scale offer considerable promise but must be enhanced and expanded for application to large systems before significant increases in productivity and reliability and reductions in cost can be realized. With the ultimate goal of fully automatic software generation, this area of software technology will yield tools and techniques to assist software engineers in specifying requirements, transforming requirements into formal specifications, generating alternative designs, integrating reusable components, generating code and documentation, verifying and validating the resultant code, and providing traceability to the requirements throughout the process.

Secure and trusted software has lagged behind the development of other areas of software technology but is increasing in criticality with the size and complexity of the software in defense systems. DoD must take the lead in secure and trusted software research since security is frequently outweighed economically in the commercial marketplace by other requirements. Significant improvements in system security, reliability, and safety can accrue as a result of research in this area. Key elements of research include identifying vulnerabilities and countermeasures, specifying a mathematically based definition of trust and trust metrics, developing multi-level secure distributed operating systems and trusted data bases, and developing trusted software methodologies, formal verification tools, and distribution strategies.

Research in software for parallel and heterogeneous distributed systems will entail the development of new system software (e.g., operating systems, languages, compilers, debuggers, and other tools) to support successful applications software development. Massively parallel computation, useful for scientific and engineering calculations, requires new algorithms and programming methodologies. New programming languages based on nontraditional computational models (such as dataflow) and advanced compiling techniques will maximize the use of all of the parallelism available in scientific and signal processing applications, without requiring explicit programmer optimization. New tools and methodologies for effective software development on heterogeneous distributed systems (particularly for embedded systems) are needed. The exploitation of complex parallel and distributed systems offers orders of magnitude improvements in availability and dependability of weapon systems and potential spin-off to the industrial base in communication, data processing, and engineering design. (See also Section 3 on parallel computer architectures.)

Software and system engineering environments that utilize and support standard interfaces, allow for the integration of commercial products, promote the development of modular reusable software, and assist in the development of standardized programming paradigms. High quality in this area has the potential to cut development and support costs considerably by improving the productivity of software engineers and by increasing the transportability of software tools across environments. Software management tools and techniques are needed to provide greater visibility into software products and processes (including cost, schedule, and performance parameters); identify, assess, and control software risks throughout the system life cycle; and aid in the consistent definition and application of software metrics. Software re-engineering tools and techniques should be explored as a means to retrofit appropriate portions of DoD's huge inventory of antiquated software with new technologies. At a higher level, pursuit of an integrated system support environment encompassing both hardware and software aspects of system engineering will contribute to the optimization of the allocation of system functionality between hardware and software. A theoretical basis for optimizing functional allocation between hardware and software, and the tools for managing this trade-off process, have yet to be developed.

Real-time/fault-tolerant software technologies involve methods to tailor runtime environments to increase real-time performance, benchmark performance, construct reliability indicators, and develop programming techniques to allow graceful degradation of a system. There are real-time aspects to nearly all DoD weapons, platforms, and communication systems.

2. Potential Benefits to Industrial Base

From the 1940s through the 1960s, DoD was a major consumer of software technology. Defense requirements were an important force in the US marketplace; however, this situation is no longer true. Most of today's commercial software products are targeted to commercial and scientific customers. DoD must now exploit commercial off-the-shelf products and make maximum use of those that meet military needs. This approach will result in an increased reliance on software that is reusable, portable, and built on commercial off-the-shelf products and takes advantage of standards in an open systems environment. The movement to open systems (instigated by major commercial software customers such as the automotive industry) has gradually won the support of major computer and software vendors. Significant opportunities exist for US companies to broaden their market share and to compete equitably in the international market through the development of products adhering to open systems standards being specified by a number of groups, including the Institute of Electrical and Electronics Engineers (IEEE).

The Ada language is an example of defense technology that has significantly affected the industrial base. DoD's development of and commitment to Ada has spawned a new industry, contributing to the start-up and expansion of numerous US companies. As of December 1989, 48 companies were sponsoring 292 validated Ada compilers. Ada has been adopted as the language of choice for certain applications worldwide, creating an international market for Ada products and services. And, perhaps most significantly, utilization of the Ada language has promoted the adoption of modern software engineering practices across the software industry.

C. S&T PROGRAMS

1. Milestones

Milestones--Software Producibility

Technical Area	By 1995	By 2000	By 2005
Reusable software	• Develop metrics for measuring software reuse • Develop tools for validation and verification of reusable software components • Develop DoD-wide guidelines for the development and reuse of reusable software components • Establish reuse repositories for specifications, designs, code, and documentation • Develop incentives for promoting DoD access to reusable software components developed by the private sector • Establish specifications for reusability domains	• Achieve 20% of software components in the development of major new systems • Develop index of reuse libraries for each domain • Develop public and classified libraries for each domain • Automatic identification of reusable software components for development of major systems	• Achieve 50% reuse of software components in the development of major new systems
Automatic software generation	• Improve representational forms for requirements to provide semi-automatic transformation of requirements into prototype designs • Provide fully automated documentation generation • Develop automated algorithm optimization techniques analysis	• Develop semi-automatic techniques for the transformation and optimization of prototypes into production quality software	• Provide an environment for fully automated software program generation from high-level specifications for sequential computer applications
Secure and trusted software	• Develop a trusted software engineering environment in compliance with DoD 5000.28-STD (Orange Book) • Develop prototype tools for the validation and verification of trusted software code	• Develop a design for assured service for various types of distributed systems in accordance with the Orange Book • Develop a library of reusable trusted software code • Develop and apply methods, techniques, and tools to facilitate the integration of security requirements into the system life cycle	• Develop an engineering environment for the automated identification and utilization of reusable trusted software code for major systems in accordance with the Orange Book • Demonstrate significant improvements in reuse of trusted software code from 1995 levels

(Continued)

Milestones--Software Producibility (Continued)

Technical Area	By 1995	By 2000	By 2005
Software for parallel and heterogeneous distributed systems	• Develop requirements specifications for software engineering environments based on viable parallel computer architecture approaches • Start development of one or more parallel programming languages based on existing techniques • Develop parallel algorithms for DoD applications areas • Develop software tools for parallel processing similar to those for conventional software development but incorporating parallel algorithms • Develop a systems software base for heterogeneous distributed and parallel systems • Develop, evaluate, and analyze software environments that enhance large distributed systems and system concurrency • Formalize a scientific basis for the design and effective utilization of advanced parallel and distributed computer systems • Develop tools, techniques, and prototypes for the design and development of computer systems with truly distributed architectures	• Demonstrate prototype software engineering environments for parallel processing that support teraops computing (one billion floating-point operations per second) • Enhance existing and develop new programming languages and environments for parallel computing • Develop advanced software engineering techniques for heterogeneous distributed and parallel systems • Provide software development environments for empirically developing distributed concurrent systems	• Develop software engineering environments for parallel processing • Demonstrate productivity through the utilization of high-level languages for parallel computing • Develop enhanced software engineering environments for distributed real-time embedded software • Demonstrate the use of software support tools, mathematical techniques, and architectures to achieve an order of magnitude productivity improvement for heterogeneous distributed systems from 1995 levels

(Continued)

Milestones--Software Producibility (Concluded)

Technical Area	By 1995	By 2000	By 2005
Software and systems engineering environments	• Build upon existing software engineering environments to include a framework for integrating commercial tools • Revise the Ada language to take advantage of new software development methodologies and tools • Develop explicit means to measure productivity and begin the collection of empirical data • Develop and demonstrate software management tools and software quality indicators to assess the status and quality of software products	• Demonstrate a factor of two reduction in residual errors for large-scale software systems from 1995 levels • Implement software support tools and methodologies resulting in an order of magnitude productivity improvement from 1995 levels	• Demonstrate knowledge-based software environments for orders of magnitude improvement in software productivity for large-scale mission-critical systems • Develop an integrated engineering support environment that addresses both hardware and software aspects of system engineering
Real-time/fault-tolerant software	• Develop and demonstrate enhanced fault-tolerant techniques for real-time mission-critical sequential processing software systems	• Develop benchmarks for fault-tolerant real-time systems using parallel and distributed processing	• Install embedded fault-tolerant real-time systems on new mission-critical platforms using parallel and distributed processing

2. Developing the Technology

DoD sponsors a broadbased research and development program to support software design, development, evolution, and maintenance. A major effort is the Consolidated DoD Software Initiative, which consists of the Ada program, the Software Technology for Adaptable, Reliable Systems (STARS) program, and the Software Engineering Institute (SEI). The major activity of the Ada program over the next few years is a revision to the Ada language to address current essential requirements. The emphasis of the STARS program is the development of production-quality Ada reuse repositories and software engineering environments to include a framework, tools, and standard interfaces. The SEI is a federally funded research and development center established to support the goal of transferring new software engineering technology into routine common practice throughout the DoD.

In addition, the DoD technology base program sponsors developments in the following areas: distributed and parallel systems, including parallel operating systems and heterogeneous distributed computing; data bases, with an emphasis on distributed object management; algorithms, with an emphasis on exploitation of parallelism; secure and trusted software; and software tools and engineering environments. The latter activity has several areas of emphasis, including prototyping language and environment to support requirements engineering and systems design; storage mechanisms for software components, including access control and usage metering; advanced Ada technology for concurrency analysis, real-time systems, and explicit process models; scalable (useful on small and large systems) methods and tools for enhancing the quality and predictability of software, including security, safety, and functionality properties; language, analysis, optimization, and refinement tools to support scientific applications on parallel computers; (6) methods to retain and apply software design information to support rapid adaptability, and design reuse; and (7) the development of a common base of tools for data interoperability, user interaction, and heterogeneous systems development.

DoD also supports basic software research programs to develop the scientific foundations for the design of correct, efficient, and reliable software. Efforts are underway to investigate: the mathematical foundations of language semantics; new algorithms to solve combinatorial optimization problems; very high-level programming and specification languages; software verification and validation; and experimental software development environments. DoD also funds three accelerated research initiatives (ARIs) in software. The first, Foundations of Deadline-Driven Computation, started in FY89, is concerned with the theoretical underpinnings for mission-critical, real-time systems. These theoretical underpinnings include comprehensible, testable formalisms for representing and manipulating time in specification, design, implementation, and testing of real-time computing systems as well as real-time scheduling algorithms with predictable performance. The other ARIs, Foundations of Parallel Computation and Ultra-Dependable Multi-Computers, involve software technology research along with multi-processor computing architecture R&D.

Total S&T funding[2] for software producibility in FY91 is approximately $130 million. A summary of DoD funding trends is shown below.

Funding--Software Producibility ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
420	130	140	150	150	150	150

3. Utilizing the Technology

Given the pervasiveness of software technology across defense systems, DoD has a wide variety of ongoing R&D programs that utilize software technology. The following programs are among the largest (comprising more than 1 million lines of code) and most visible of these programs: the Strategic Defense System, the Army's Advanced Field Artillery Tactical Data System, the Army's Standard Finance System Redesign, the Navy's AN/BSY-2 Submarine Combat Control System, and the Air Force's Advanced Tactical Fighter.

2 Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

Manufacturing and industrial base concerns are not related to software contained in weapon systems but to the software used to plan, schedule, and control the manufacturing of weapons systems. Two aspects of software technology are important to the manufacturing and industrial base area: architectures and development techniques for the creation of new software and those appropriate to the more effective utilization and reuse of the existing software base. R&D in high-level languages, computer-aided software engineering tools, and modular software will contribute significantly to the efficiency with which software is produced and the reusability of substantial amounts of code.

The more immediate industrial base problem is caused by an estimated $500 to $700 billion in systems installed in the US manufacturing sector. These systems are critical to the performance of the US manufacturing sector, and will take many years to replace regardless of the advanced capabilities on the market. Research and development are needed to provide the basis for cost effectively upgrading these systems without significant disruption to continued operations. Technology resulting from efforts in this area are applicable to virtually the entire US industrial base as well as large elements of the service industries. Current DoD efforts in the area include elements of the Sematech consortium (an industry consortium initiated and partially funded by DoD), the Computer-Aided Logistics System program, and portions of the Air Force Manufacturing Technology Program. DoD R&D funding in FY90 for such efforts is estimated at approximately $70 million; industry funding is estimated to be three to four times that amount.

2. Projected Manufacturing Capabilities

Large-scale, continuing efforts are required to develop the technologies necessary to smoothly integrate the wide variation of computers, operating systems, application software, and user interfaces in daily use. A framework for information integration, formed by national consensus, is needed, as are the standards required to implement such a framework. Accomplishing this task will require an investment in excess of $1 billion in technology and standards alone. The computer, software, and systems integration industries will be the sources for such developments and may be expected to invest four to five times as much in the creation of products which embody and support the technologies and standards.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

Historically, the aerospace industries in the United States and abroad have not put significant resources into software R&D. As a result, promising technology in laboratories and universities has not been put into products or practice. The government agencies, both civilian and military, have usually sponsored the lion's share of the R&D performed by government, university, and industrial laboratories. The National Science Foundation (NSF) sponsors basic research in software technology, with an emphasis on theory.

Although moderate-scale prototype engineering activity is occasionally undertaken, most NSF support is provided to individual researchers working on theoretical problems.

Federal investment in Ada language research and implementation is increasing. On October 20, 1989, the Federal Aviation Administration issued an action notice prescribing Ada as the single, common, high-order programming language to be used in the acquisition of air traffic control subsystems with the national airspace system. The National Aeronautics and Space Administration (NASA) is considering a similar proposal to mandate Ada for all mission-critical software. NASA is already utilizing Ada on the Space Station Freedom Program and is sponsoring a major Ada-based software engineering environment. There is significant potential for collaborative Ada research efforts and the sharing of reusable Ada software.

Software is a subject of considerable interest within both the executive and legislative branches of the US government. A report issued in April 1989 by the Congressional Office of Technology Assessment, entitled "Holding the Edge, Maintaining the Defense Technology Base" includes a software case study based on the assumption that software is a dual-use technology, that it "can have multiple, significant applications to military systems, and that it can be employed extensively in civilian industry as well." The study found a "high degree of technological convergence between civilian and military applications. . . .In the case of software, DoD simply does not have access to the best and most advanced civilian talent and products, and there is very little synergy between the military and civilian components of this critical high technology industry."

The Subcommittee on Investigations and Oversight of the House Committee on Science, Space, and Technology issued a report in August 1989, entitled, "Bugs in the Program: Problems in Federal Government Computer Software Development and Regulation." The report stated that "the [White House] Office of Science and Technology Policy (OSTP) should oversee a program of long-term interagency coordination and cooperation in software. Many Federal agencies have already worked through the pitfalls of increasing complexity in software systems, but other agencies are not benefitting from that experience."

In September 1989, OSTP published the "National High Performance Computing Initiative Research and Development Implementation Plan." The plan identifies advanced software technology and algorithms as one of four complementary, coordinated components of the high performance computing initiative and states that "an interagency effort will be established to support joint research among government, industry, and universities to improve basic software tools, data management, languages, algorithms, and associated computational theory."

2. R&D in the Private Sector

The following commercial product developments are under way that should contribute to software producibility if utilized by DoD:

- New data base technology, especially for the management of objects over a distributed network
- Libraries of reliable, reusable program components, now possible due to object-oriented technology
- Continuing improvement in computer-aided software engineering (CASE) tools.

Several industrial consortia have been formed to address aspects of software technology, such as the Software Productivity Consortium and the Microelectronics and Computer Technology Corporation.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

The following technologies are indicative of the capability of a nation in software technology.

- Software development environments, especially object-oriented automation of requirements and cost analysis, rapid prototyping, and associated library and management support capabilities
- Operating systems and applications to support real-time information management in large, distributed computer operations
- Algorithms, languages, and software engineering tools to take full advantage of the performance potential offered by advanced computer architectures. (See also the section above on parallel computing architectures.)

The table on the following page provides a summary comparison of the United States and other nations for selected aspects of the technology.

The USSR has demonstrated strong theoretical capabilities in computer science. Software technology, however, continues to be an area of serious deficiency, much of it stemming from a shortage of computers, especially microcomputers and supercomputers, and from reliability problems, especially with peripherals. Soviet programmers lack adequate hands-on computer experience. Computer-to-computer networking is rare except in high-priority applications. The situation is exacerbated by the poor quality of public telecommunications and poor technical communications among S&T professionals.

There has, however, been a conspicuous trend in the Soviet military literature, beginning in the early 1960s, to stress cybernetics and operations research as elements in military decision making The literature refers to the computer as a "comrade-in-arms," in addition to acknowledging its role as a consultant and information source. The issue of computer security has become as important to the Soviets as it has to the United States. It is unlikely, though, that Soviet computer security is any better than that of the United States.

The European and Japanese communities are developing partnerships among government, industry, and academia at a much faster pace than the United States. However, the research into software technology in the United States is probably better than research in Japan and Europe. Opportunities for cooperation within NATO and Japan include niche areas associated primarily with supercomputing, specialized methods for exploiting massively parallel architectures, and formal methods for highly reliable and portable software. There are two ongoing cooperative efforts to develop standard interfaces for Ada programming support environments. Under the auspices of the Nunn amendment, ten NATO nations are implementing the DoD-developed Common Ada Programming Support Environment (APSE) Interface Set, Revision A (CAIS-A) and a toolset on two hardware architectures to demonstrate the portability of tools using standard interfaces. In a companion effort, the convergence of CAIS-A and the European-developed Portable Common Tool Environment+ (PCTE+) interface standard is being examined.

The Japanese have started the anti-software crisis project to develop an effective approach to software engineering. Japanese companies are also developing an operating system for distributed real-time processing for their new generation of 32- and 64-bit microprocessors.

The NATO countries have strong capabilities in selected areas of software technology. NATO has adopted Ada as a standard programming language and individual NATO countries have either adopted or mandated the use of Ada in military systems. No single country has competence in as many technologies as the United States. Software development has been an area of emphasis, and multinational ventures in Europe have the potential for achieving comparability with the United States by combining individual strengths. Large-scale European projects are sponsored by the European Strategic Program for Research in Information Technology (ESPRIT) and European Research Coordination Agency (EUREKA), using joint industrial and government funding. Planning documents indicate that approximately 20 percent of the budget for these consortia is allocated to software, not including office systems and artificial intelligence. The EUREKA program, with a total cost of about 4 billion European currency units (ECUs), promotes collaboration through coordination; funding is provided by the industrial participants. Explicit emphasis is given in ESPRIT to the development of common software interfaces (e.g., PCTE+) and portable tools. Additional emphasis on the use of formal methods to develop highly reliable software has led to a European lead in many areas.

In addition to ESPRIT and EUREKA, individual European countries have their own programs, such as the Alvey program in the UK, which has produced effective ongoing collaborations between industry and universities. Among the NATO nations, the UK evidences perhaps the greatest interest and capability in developing software engineering tools and languages for massively parallel architectures. The Netherlands and the FRG also have extensive efforts addressing a wide range of software engineering topics, including algorithms and software for parallel architectures.

Outside of NATO and Japan, virtually all industrialized nations have some efforts relating to the development of specific algorithms, including research into optimizing the performance of such algorithms on parallel machines. The nature of this research lends itself to individual breakthroughs in specific algorithms. These may contribute to significant advances beyond existing US capabilities, but cannot be predicted or planned for in advance.

2. Exchange Agreements

The NATO Defence Research Group (DRG) programs in operations research and long-term research for air defense provide a mechanism for exchanges of information on requirements for improved software technology. The Technology Cooperation Program (TTCP) sponsors a group on software engineering as well as a range of other applicable exchange activities, including computing technology, trusted computer systems, and machine and system architecture. The Services also have exchange activities, primarily with NATO nations. Ongoing Service exchange programs in software development methodologies, techniques and tools; distributed command and control, signal processing, flight control, and cockpit systems for advanced fighters and helicopters; and computational fluid dynamics contribute directly to the US understanding of foreign software engineering technologies. The following are specific MOU's on Ada technology.

- Memorandum of Understanding between the Ministry of Industry of France and the DoD of the United States of America for Exchange of Ada Program Technical Information and Establishment of an Ada Validation Facility, January 23, 1987

- Memorandum of Understanding between the Federal Ministry of Defense of the Federal Republic of Germany and the DoD of the United States of America for Exchange of Ada Program Technical Information and Establishment of an Ada Validation Facility, February 17, 1987

- Memorandum of Understanding between the Ministry of Defence of the Government of Sweden and the DoD of the United States of America Concerning Technical Information for Information Exchange for Compatible Ada Programming Support Environments, June 1, 1987.

Summary Comparison--Software Producibility

Selected Examples	USSR	NATO Allies	Japan	Others
Enhanced software development environments	▨	□□□	□□□	
Operating systems and applications software to support real-time information management in large, distributed systems	▨	□□	□□	
Algorithms, languages, and tools for advanced parallel architectures	▨	□□	□□□	□□[a]
OVERALL EVALUATION[b]	▨	□□	□□	□□

[a] Many countries have ongoing theoretical work in algorithms. Individual breakthroughs are possible from any of these efforts, but cannot be predicted or planned.

[b] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of allies to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

3. PARALLEL COMPUTER ARCHITECTURES

A. DESCRIPTION OF TECHNOLOGY

Rapid improvements in the performance of computer hardware without increase in cost have spread computing into all areas of military and civilian life. Such rapid improvements in the speed of computing have come primarily from advances in the understanding of the physics and fabrication of electronic materials and devices. As the fundamental speed limits of materials properties are approached, further significant speedup is more likely to come from new approaches. Average speed increases of 50 percent per year, sustained for the past 30 years, have produced computers capable of executing 10 to 20 billion operations per second. Advanced computer architectures will play a key role in maintaining this momentum. Cost reductions have made large-scale parallel systems feasible, opening a path to systems of even higher performance, and performance is expected to exceed one trillion operations per second over the next few years.

Critical Technology Challenges for Parallel Computer Architectures

- Integration of heterogeneous processor elements
- Architectural design
- Integration of special-purpose systems and devices
- Algorithms, tools, and languages
- Specialized compiling, operating, and debugging software

In general, this technology area encompasses product design technologies, though some related manufacturing technology challenges exist, such as wafer-scale integration. The major technology challenges listed above can be detailed as follows:

- Integrating heterogeneous processor elements required for digital, symbolic, and signal processing parallel architectures.
- Optimizing the performance of scalable parallel computing systems by developing optimal architectures and internal communication structures.
- Integrating special-purpose ultra-performance (a tenfold increase in generic system performance) components into general-purpose systems.
- Developing algorithmic approaches, which utilize parallel computation effectively, and techniques for vectorization of algorithms.
- Developing effective compiling, operating, and debugging software for parallel architectures.
- Developing parallel software development techniques, languages, and environments. (This entails developing robust, user friendly operating

environments together with a mathematical infrastructure for parallel computation.).

- Developing performance analysis capabilities for the design of high-performance, real-time parallel processing systems.

B. PAYOFF

1. Impact on Future Weapons Systems

Computer system technology is expected to continue to provide a critical edge in performance for all classes of weapons and command and control systems. Weapon system accuracy and corresponding lethality, plus improved performance in naval, ground, and air vehicles, will be significantly enhanced through the exploitation of parallel computer architectures. High-performance parallel computing will enhance DoD weapon systems in two primary ways. First, utilization of powerful parallel machines in the design of the weapon systems themselves and of the platforms that deliver these systems will result in more effective individual weapon systems and lower amortized cost per system. These improvements will occur through anticipated advancements in materials science, computational fluid dynamics, semiconductor design, and machine vision that are enabled by high performance parallel computers. For example, strategic defense system simulation will exploit a variety of parallel computer architectures. Highly reliable, space-qualified embedded parallel processors are being developed for elements of the strategic defense system, and current commercial parallel processors are very applicable to ground-based processing requirements.

Second, larger military platforms will be able to carry high-performance parallel processors and be able to execute currently infeasible computations while in an operational status. Shipboard signal processing vastly superior to current Airborne Warning and Control System (AWACS) aircraft functionality is conceivable. Similarly, the notions of "smart hulls" for submarines and "smart skins" for aircraft are dependent on high-performance, parallel computing systems. High-performance, embedded systems are also crucial for automatic target recognition capability by smart weapons. One-thousand-fold performance increases over present computer systems would find immediate application in large-array, ASW systems. Finally, parallel computing can enable predictive modeling of atmospheric and oceanographic events, which can have a tremendous effect on the employment of advanced weapons systems.

2. Potential Benefits to Industrial Base

High-performance parallel computing will significantly affect the industrial base because of the increasing use of computation to augment experimental and theoretical approaches to science and engineering. Parallel computer designs may be scaled over a wide performance range (scale factor of 1,000 or more from the smallest system to the largest). These systems are also more effective in terms of cost, performance, volume, and power than conventional high-performance computers. The first generation of parallel computer systems has recently emerged in commercial products in large part as a result of Defense Advanced Research Projects Agency (DARPA) investments. The second generation is currently under development, with systems expected to emerge in 1992. High-performance computing realized as scalable parallel, distributed systems with associated networking technology, systems software, software development environment, and trained personnel represents a fundamental enabling technology for the United States in the new information technology age.

Markets and applications will drive industrial investments in parallel computer architecture technology. By 1995, the top five markets will be government, aerospace, petroproducts, electronics, and research. Applications of this technology include computer-aided design, computer-aided manufacturing, numerically controlled machine control, computer-aided engineering, and simulation and modeling. US airframe manufacturers are already using massively parallel processing to replace expensive wind tunnel and radar range tests in aircraft design and are developing engineering simulation software that can also be run on training simulations.

C. S&T PROGRAMS

1. Milestones

Milestones--Parallel Computer Architectures

Technical Area	By 1995	By 2000	By 2005
System throughput	• Teraops systems • 100 Gigaop embedded (Giga = 10^9)	• 100 Teraops systems • Teraop embedded (Tera = 10^{12})	• Systems capable of 10^{15} operations per second
Optics	• 3-D memory • Optical routing		
Operating system	• Real-time parallel operating system	• Trusted real-time, parallel operating system	
Hardware	• Wafer-scale package • Widespread use of parallel applications	• Rapid manufacturing for special purpose	• Flexible reconfigurable hardware architecture

2. Developing the Technology

Computing systems are being developed that will achieve 1,000-fold performance increases with greater reliability and density, lower cost (factors of 10 to 20), and higher density through parallelism, i.e., use of many subsystems solving various parts of the information-processing problem at the same time, combined with advanced modular packaging techniques. Prototypes are now in place that compute at rates of billions of operations per second (gigaops) and have roughly 1,000 times the throughput of computing systems now used in defense systems. By the mid-1990s, systems capable of trillions of operations per second (teraops) will be available. By the year 2000, qualitatively new capabilities such as autonomous vehicles, automated image analysis for intelligence, and reduction of planning cycles from days to minutes are expected.

DoD has developed a number of parallel architecture processors, such as the Enhanced Modular Signal Processor and the ASPRO special-purpose processor, intended for digital signal processing applications. Both of these machines are being produced in quantity and are in service in the Navy. A significant accomplishment in DoD research is the invention and exploitation of so-called *systolic* techniques for solving many numerical and symbolic problems. DoD investment in multi-processor technology through multi-processor design and packaging efforts at Lawrence Livermore Laboratory has resulted in a substantially deeper understanding of very large-scale integrated (VLSI) design techniques and multi-processor packaging.

DoD has a strong basic research program to discover new parallel procedures for solving many categories of computationally challenging problems. DoD also supports a substantial amount of basic research in parallel computing software development strategies and the difficult issues involved in parallel programming verification, software instrumentation, and resource management for real-time applications. In addition, DoD is focusing on the important problem of improving multiprocessor system-level dependability through research in topics such as algorithm-based fault-tolerance, dynamic architectural reconfiguration, and data dispersal techniques.

Total S&T funding[3] in this critical technology is shown below.

Funding--Parallel Computer Architectures ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
250	120	140	150	150	150	150

3. Utilizing the Technology

DoD is a major current and future user of high-performance parallel computing technology. The DoD laboratories exploit parallel machines for a wide variety of numerical and symbolic computations in ASW, quantum physics, fluid dynamics, and natural language understanding. Intensive activity is underway to determine whether systolic processors can also be employed in ASW signal processing. The AN/BSY-2 submarine combat control system currently under development uses a loosely coupled parallel processor design. DoD is also using parallel computing to support development of the next-generation tactical fighter aircraft. In addition, parallel processors have been demonstrated or will be exploited for standoff minefield detection, multi-sensor target, acquisition demonstration, distributed communications systems, and distributed C^2-force level control.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

First-generation scalable parallel systems are now commercially available from US vendors. Makers of parallel computing equipment fall into two principle categories:

3 Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

supercomputer vendors (there are 6 domestic firms) and minisupercomputer vendors (approximately 23). The market for supercomputers is estimated to grow 7 percent annually from 1989 to 1992, while the minisupercomputer market will grow 28 percent annually during the same period. DoD-sponsored investments in manufacturing technology are focused on microelectronic needs (VHSIC, wafer preparation and packaging, integrated circuit manufacturing).

2. Projected Manufacturing Capabilities

Specific plans related to manufacturing technology will be driven by growing market pull from large commercial and scientific markets that were once the exclusive domain of the mainframe and are moving rapidly to parallel processing. Most US-based supercomputers and nearly all minisupercomputers have parallel architectures. The mainframe trend is also clear; the IBM 3090 is a parallel architecture computer. It is estimated that nearly half of the systems shipped in 1991 will contain parallel architectures. Because of increased emphasis on advanced computing by Japanese computer manufacturers (with strong government backing), a highly competitive environment will be evident.

No special manufacturing needs to dictate development of parallel computer architectures; however, the United States must have the memory chips to utilize this high-speed computing technology. Other related industries and technologies include software, distributed data bases, parallel and distributed computation, computer-human interface, and networking and communication.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

The DoE has active programs in a number of parallel computer architecture areas:

- Robust computing infrastructures
- Methods development and implementation for major applications
- A small number of experimental supercomputing centers established through the national laboratories
- Use of government research centers in educational initiatives.

DoE in particular is fostering education through a series of post-doctoral and pre-doctoral fellowships, through its efforts to provide a center for parallel computing that would be open to researchers and students from other institutions (a DARPA/INTEL/ collaboration in DARPA's Touchstone project, networking collaborations with AT&T Bell Labs, and architecture research collaborations with industrial firms). DoD research at universities focuses on parallel algorithms, software development environment and techniques for parallel machines, and instrumentation and monitoring techniques for parallel architectures. University research is also concentrating on the development of parallel programming environments to permit effective utilization of parallel computer architectures, especially for scientific computing applications. A major research program to develop an integrated programming environment for shared memory architectures is underway at the University of Illinois.

The Army has designated the University of Minnesota as the location of an Army High Performance Computing Research Center. This center is a five-year effort involving acquisition and networking of high-performance computing architectures in a heterogeneous environment, basic interdisciplinary research in the optimal exploitation of problem structure and parallel architectures in the solution of problems in science and engineering, and the transfer of expertise in parallel processing from the center to DoD scientists in an infrastructure support program of internships, on-site tutorials, consulting, technical reports, and hands-on parallel computing experience. Furthermore, the development of parallel software systems required to support the center will directly affect productivity in parallel software development, which lags far behind developments in parallel processing hardware.

2. R&D in the Private Sector

Defense investment in high-performance parallel computing has spawned a number of industrial product lines, mostly oriented toward commercial applications. Industry generally considers exploitation of massive parallelism into the teraops range as too risky for development. Instead US industry has pursued incremental improvements in older approaches to computing. University research is concentrating on the development of parallel programming environments to permit effective utilization of parallel computer architectures, especially for scientific computing applications.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Design of massively parallel, distributed computing with 10^{11} to 10^{12} FS capabilities
- Improved packaging (including interconnect and thermal management) for massively parallel hardware
- Development of software and software development tools to exploit massive parallelism
- Development of trusted operating systems for distributed, parallel computing.

The following table provides a summary comparison of the US and other nations for selected key aspects of the technology. The United States has a significant worldwide lead in serial production and practical application of parallel processing hardware. This lead developed from and continues to be supported by the US capability in microprocessors and a broad experience base in advanced computing hardware design and packaging.

Summary Comparison--Parallel Computer Architectures

Selected Examples	USSR	NATO Allies	Japan	Others
Design of massively-parallel, distributed computing with 10^{11}-10^{12} FLOP capabilities	▨	□□	□□	
Improved packaging (including interconnect and thermal management) and massively parallel hardware	▨	□□	□□□	□□ Switzerland
Development of software and development tools to exploit massive parallelism	▨	□□□	□□□	□□ Israel, Hungary
Development of trusted operating system for distributed, parallel computing	▨	□□	□□	
Overall [a]	▨	□□	□□	□□ Switzerland, Israel, Hungary

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

There is no evidence that the USSR has achieved significant success in high-performance computing. The Soviets have historically followed the United States by 10 or more years in computer systems, and there is no indication this will change. The Soviets are, and will continue to be, severely hampered by lack of capability for quantity production of high-speed digital components and assemblies (see Section 1, microcircuits). Thus, their strengths are likely to remain largely in theory, research, and prototyping. While the Soviets have a significant effort in parallel computing, they are many years from being able to provide their scientists and engineers with the levels of technology presently available to their Western counterparts.

When compared to the United States, European and Canadian parallel computing efforts are strong and growing, while Japanese efforts appear to be trailing. Still, the United States does not have access to the latest Japanese advances. Furthermore, US technology builds on and is highly dependent on underlying Japanese component technology--especially memory chips. Cooperative opportunities will exist with NATO countries, especially with the UK, the Netherlands, the FRG, and France.

Japan, the UK, Netherlands, and FRG all have credible efforts in parallel computing. The Japanese are the most advanced and, in fact, currently hold the lead in performance of production models of previous generations of computer systems (with limited or no parallel computing). The Japanese are a few years behind the US in highly parallel systems, particularly in the area of system software, but can be expected to close the gap rapidly as significant commercial advantage develops in this area.

Japanese R&D in parallel computing is beginning to show results. The Industrial Technology Agency's Electrotechnology Laboratory has recently announced the development of a 128-processor configuration data flow system, the Sigma-1. The stated maximum processing speed is 640 million floating point operations per second (MFLOPS), placing the system in the supercomputer category.

The UK has a significant parallel processing software research effort and infrastructure in its universities, industry, and government establishments. Notable among these is the Alvey Program for Advanced Information Technology. The European Strategic Program for Research in Information Technology (ESPRIT) is also pursuing related software engineering initiatives. Specific areas of research include techniques for dynamic control of array topology and diagnosis and control of load balance in massively parallel processors. The Edinburgh concurrent supercomputer is presently using an electronically reconfigurable 200-processor array of Inmos transputers for a wide range of research and modeling applications. The ESPRIT project also uses the Inmos transputer and supports research in many areas. Applications include development of high-level programming languages and techniques for image processing and synthesis, scientific computation (including computational fluid dynamics), logic simulation, and artificial neural nets.

The UK was a primary contributor to the development of the OCCAM programming language--the first general computer language written specifically for parallel computers. Inmos, Limited (Bristol, England) developed and now produces a line of VLSI chips specifically designed to implement the OCCAM language. These transputers are the building blocks of a research program being pursued by the Royal Signals and Radar Establishment with support from Thorn EMI, Ltd., Inmos, and Southampton University to develop a real-time reconfigurable supercomputer.

Recently the Netherlands has become much more active in the field, especially in the areas of algorithms and the application of parallel architectures to artificial intelligence.

2. Exchange Agreements

Mechanisms for international cooperation in military applications of parallel computing are still developing in this relatively new field. The NATO Defense Research group (DRG) programs in operation research and in long-term research for air defense provide a mechanism for exchanges of information to help understand and define essential requirements for future applications of parallel computing. The Technology Cooperation

Program (TTCP) provides a direct vehicle under its program for machine and system architecture and for a range of applicable exchange activities under computing technology, software engineering, and trusted computer systems. These programs, together with technology exchanges in basic electronics, should also contribute to overcoming packaging and thermal management problems in assemblies with the extremely high component densities typical of massively parallel machines.

The Services also have exchanges, primarily with NATO and a few other friendly nations. Ongoing Service exchange programs in distributed command and control, signal processing, flight control, cockpit systems for advanced fighters and helicopters, and computational fluid dynamics support in parallel computer architecture technology.

4. MACHINE INTELLIGENCE AND ROBOTICS

A. DESCRIPTION OF TECHNOLOGY

Machine intelligence and robotics are related technologies with rapidly growing applications in modern, high-performance, and complex weapons. While few complex weapons can be described as robots, many involve robotic technology. These weapons are tightly coupled man-machine systems, carefully designed to make effective use of the unique capabilities of both man and machine. In some cases, robotics and machine intelligence, when coupled with advances in compact computers, may obviate all human presence in dangerous environments. In other cases, enhancing the man-machine link may prove the difference between victory and defeat in combat.

Machine intelligence, the capability of computer systems to mimic and augment human intelligence, has the potential to provide dramatic advances to human decision making through automated aids. As the basis for the controlling software in robotic systems, machine intelligence techniques also will allow the fielding of robots that can be relied upon to perform and survive (when substituted for humans) in remote or dangerous environments. The enhanced performance, multiple-use, and improved quality of design offered by machine intelligence and robotics justify its selection as a critical technology.

The design of intelligent machines and robots requires combining the technologies of sensing, cognition, and action with a suitable man-machine interface. Therefore, this critical technology utilizes the results from many other technologies. Intelligent machines will increasingly depend on advances in parallel computer architectures (for rapid control), software producibility (to handle the complexity of sensing and control), sensors (to provide inputs to intelligent action), data fusion (to combine the signals from many sensors), and composite materials (to permit light weight).

Components of machine intelligence technology already have proven their commercial worth in moderately complex applications. Expert systems, for example, provide advice and problem-solving skill in specialized, well-constrained knowledge areas and are routinely used in medicine, electronic troubleshooting, product evaluation, and financial analysis. Expert systems are beginning to proliferate within the DoD (with more then 70 known operational or prototype systems in DoD). In addition, several vendors now market natural language understanding (NLU) systems to support efficient human-computer interaction with data bases. As the basis for an improved interface to data bases, NLU technology allows the use of ordinary English in asking questions, receiving answers, and updating stored data. Also, speech recognition and computer vision (especially in robotics and manufacturing areas) are beginning to make notable contributions.

Critical technology challenges include knowledge acquisition, knowledge representation, automated reasoning, improved man-machine interfaces, and training.

Knowledge acquisition addresses the means by which intelligent systems can acquire the information essential to their tasks, and ranges from the approach of knowledge engineering (which requires programming by humans) to entirely automated learning through sophisticated inference. Knowledge representation addresses the possible encodings of information within the computer and seeks to understand their individual benefits and integration. Automated reasoning studies the automation of inference, such as deduction (the basis for conventional expert systems), analogical inference (a potential basis for problem-solving in future expert systems), and induction (the ability to generalize from past experience). These are not disjointed concerns; knowledge acquisition in expert systems will depend on progress in the automation of inductive reasoning, which in turn will be influenced by the availability of suitable knowledge representations.

Robotics technology also involves creating and controlling complex motion, often coordinating more than one degree of freedom, to perform desired military or manufacturing operations. Robotics mechanisms find a broad spectrum of applications in helicopters, ground vehicles, weapons systems, and robotic worktables and devices. Developing articulated mechanical devices is a critical challenge facing robotics technology. These devices are major components in military vehicles that have rotating turrets, elevating trunnions, recoiling barrels, and automatic ammunition handling equipment. Robotics systems are of particular interest in the welding of tank suspension systems, minefield breaching, refueling, reloading devices, and armament systems. A summary of the critical technology challenges in machine intelligence and robotics is provided in the table below.

Critical Technology Challenges in Machine Intelligence and Robotics

- Knowledge acquisition and representation
- Automated reasoning
- Man-machine interface
- Training
- Articulated mechanical devices

B. PAYOFF

1. Impact on Future Weapon Systems

The battlefield of the future will be fast paced. Sensors and weapons will identify targets on a real-time basis. Intelligent machines will fuse, process, and analyze data and present usable results almost instantaneously. Development of algorithms and associated software to make such systems possible is a major challenge.

Efforts also are underway to develop complex decision-making aids--a battlefield management system (BMS). By processing huge amounts of information, machine intelligence can provide much more efficient tools for effective military intelligence, data analysis, battle management assessment, timely decision making, rapid replanning, and survivability through distribution of tasking, machines, and data repositories. Thus, machine intelligence and robotics applications will reduce the need for manpower while improving human response times. Additional advantages will result from the use of autonomous robotic ground vehicles and unmanned aerial vehicles. Removing crews from hazardous environments and exposed platforms also will improve survivability.

Intelligent self-diagnostic on-line and off-line systems will improve readiness and reduce maintenance and logistics costs.

With the introduction of composite materials into the design of robotic manipulator arms, the structural weight of the manipulator and the power requirements to operate the arm at high speed will be significantly reduced. These robotic devices (with lighter components) will accomplish missions such as weapon loading, minefield breaching, materials handling, refueling, and assembly more rapidly and with less power consumption. Understanding the dynamic response characteristics of robotic systems with components fabricated from high-strength composite materials will lead to the development of control procedures that will ensure the precise positioning of end effectors in compliant robotic devices.

In military systems of the future, machine intelligence and robotics technologies will comprise highly integrated subsystems that can sense the outside world from several different perspectives (sensor fusion) and respond through processing of behavioral knowledge and control actuators to perform specific purposes. These intelligent and, where necessary, hardened machines of the future will provide an efficient means to supplement, augment, and support human capabilities when exposed to hazardous conditions.

When combined with other critical technologies (such as microelectronics fabrication technology, and parallel computing technology), machine intelligence will improve automatic target recognition capabilities, allow truly effective diagnostic and prognostic systems, create tactical decision aids, and produce advanced robotic systems. The integration of these technologies will have a significant effect in improving the selectivity and use of sensory inputs. Such improvements also will facilitate image understanding and contribute to the new area of speech recognition.

2. Potential Benefits to Industrial Base

The biggest users of robots in the US commercial sector are the auto industry and the electronics industry. Robots perform highly repetitive tasks (such as spot welding in the auto industry and automatic pin insertion in the electronics industry). Industrial robotic systems also manufacture DoD materiel.

There are widespread industrial applications for machine intelligence and robotics, ranging from the handling of hazardous materials to automation in manufacturing. Expert systems are beginning to play a significant role in the design of complex objects to be fabricated, both in verifying designs suggested by human engineers and in suggesting novel designs autonomously. Robots, already used in simple parts assembly, will become increasingly adaptable to new tasks. Machine intelligence approaches to problem solving also will yield software for the automated planning and control of factory processes, from materials acquisition to product distribution. Robotic skills in dexterous manipulation will be supplemented by the rapid recognition and examination of objects through image understanding and tactical information processing.

Application of robotics and intelligent machines in manufacturing environments will result in flexible manufacturing capabilities with shortened set-up and production lead times, greater industrial base surge capabilities/capacity, enhanced quality, and reduced acquisition costs. Intelligent self-diagnostic on-line and off-line systems will improve readiness and reduce maintenance and logistics costs. For example, recent studies have shown that man-machine interface capabilities (driven by expert system diagnostics) can reduce maintenance manhours by as much as 30 percent, component false removals by 50 percent, and maintenance test flight requirements by 50 percent.

C. S&T PROGRAMS

1. Milestones

Major milestones for this critical technology area are listed in the table below.

Milestones--Machine Intelligence and Robotics

Technical Area	By 1995	By 2000	By 2005
Unmanned ground vehicle	• One operator controls two RCVs	• Robotic combat vehicle (one operator controls five RCVs) • Robot vehicle networking and interfacing family of RCVs	• Substantially expanded autonomous operation of unmanned ground vehicles
Robotic manipulator	• Field demonstration of tank loading	• Light-weight robotic vehicle	• Widespread use of robotics throughout weapons systems
Data rate reduction	• Telerobotic vehicle • Automatic planning and control of assembly from CAD models	• Robotic security patrol with remote display and control • Autonomous capability to reason and react	• Continuing reduction in size and increase in power of data reduction capabilities

2. Developing the Technology

The man-machine interface has become of vital concern in the age of advanced technology weapons and robotics. Man-machine interactions are important not only for specific combatants (e.g., pilots and tank commanders), but also for system logistics, diagnostics and maintenance, battle management assets, and hazardous material handling. Current DoD efforts include addressing on-board diagnostic systems for the M-1 tank, AH-64 and UH-60 helicopters, and for a variety of missile systems. The advantages to be gained in terms of battlefield readiness are significant, but the potential dollars and manpower savings in operation and support costs are even more important.

DoD also manages a substantial basic research program in intelligent systems, which includes a machine intelligence component and a robotics component. The machine intelligence component has major research thrusts in deductive reasoning, with a focus on issues involving large knowledge bases; real-time problem solving and uncertainty; reasoning to support knowledge acquisition; coordination among multiple intelligent systems; natural language understanding for human-machine interaction and text processing; and neural network approaches to high-level reasoning. The robotics component emphasizes tactile information processing in conjunction with research in the design and control of dextrous manipulators and spatial reasoning to support mobility in unpredictable, cluttered environments.

Knowledge representation efforts pervade the applications of machine intelligence. Current efforts are aimed at the following goals: developing methods for efficiently encoding and using the difficult-to-structure repertoire of knowledge sometimes called "common sense"; using analogy and past experiences to develop more robust knowledge- and model-based systems that can reason and explain solutions; efficiently representing arbitrary and interrelated spatial regions and intervals of time so that systems behavior can be described; developing methods for the reuse, extension, and integration of knowledge bases without repeating the original investment in knowledge engineering; structuring knowledge so that it can, where applicable, be used in more than one problem domain simultaneously; representing knowledge for problem-solving techniques so that it can be applied to classes of problems instead of individual problems; and efficiently and automatically passing knowledge and information in a network of distributed problem solvers. These efforts are being carried out in test beds that include development of smart unmanned aerial vehicles (UAVs), as well as unmanned ground vehicles (UGVs) and unmanned underwater vehicles (UUVs), "brilliant" (very smart) munitions, signal processing, target recognition, mission planning, and pilot associate programs.

Much of the research on the physical aspects of robotic machines and mechanisms is focused on the study of the dynamics and control of deformable mechanisms. Emphasis is placed on theoretical and experimental analysis of the vibrational behavior and stability problems associated with joint and link elasticities in computer-controlled robotic manipulators. Creation of robotics software that serves to perform the numerical calculations needed to execute the motion programming of robots with general geometric configurations is also emphasized. This software will be able to work from mission task statements and a sensor-based model of the world to develop motion among obstacles and to define the forces required for robotic actions involving contact between objects.

Total S&T funding[4] for this critical technology is shown in the following table.

Funding--Machine Intelligence and Robotics ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
540.3	120	100	100	100	100	100

3. Utilizing the Technology

Since some of the DoD's most critical problems exist in logistics, it currently is investing in the development of robotic material handling systems for logistic applications (such as acquiring replacement parts). Non-logistics applications also have achieved success to date. For example, the use of fiber-optic-guided missiles (FOG-M) offers promise regarding the potential for future tele-operated systems. Tele-operated systems

4 Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

may be used as a force multiplier in which one manned vehicle could control a fleet of tele-operated companion vehicles. Today, DoD has efforts to develop a tele-operated mobile platform (TMP) that can serve as an unmanned reconnaissance platform. Another important application of a tele-operated robot will be the development of Caleb, a small vehicle capable of reconnaissance, surveillance, and target acquisition operations for the infantry. Further research will be directed at improving the man-machine interface for Caleb and developing autonomous capabilities for robots such as Caleb.

The application of expert systems and systems for natural language understanding is undergoing an acceleration due to the commercial availability of shells, software tools to assist in the capture and representation of relevant knowledge and to facilitate the selection of appropriate reasoning mechanisms. This has had the secondary beneficial effect of increasing the in-house technical understanding of machine intelligence concepts; for example, in extensive employee training programs that use expert systems on a daily basis. Over the next decade, the products of DoD's basic research and exploratory development efforts can be expected to affect weapon systems and related command and control. Many of these products are likely to lead to machine intelligence components embedded in larger conventional software systems.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

Robots play an important role in factories when used in applications such as spot welding and automatic transfer of workpieces. In certain factories, and in all of the Detroit automobile manufacturers, significant economic benefits can be achieved for applications that exhibit a large ratio of production time to programming time. Unfortunately, the current capabilities of industrial robots are limited. Machine intelligence (controller technology) will enhance and expand the applications of robots in manufacturing.

DoD investments are geared toward long-term development of new manufacturing technology in the specific area of machine tool/robotic controls which is not currently taking place in the private sector. Major developments in this area will help our industrial base and will be of advantage to the defense industry on a long-term basis. Areas the DoD currently is exploring with regard to machine tool/robotic controls include: light scattering for defects, laser triangulation for threads and defect depths, cutting tool fiber optics, neural networks, and cutting tool diagnostics. Our eventual goal is to actively work with domestic machine tool builders in the development of new manufacturing technology and to combine their technical expertise with that of DoD. DoD investments can be used to help leverage additional funding from industry and state government for these projects.

Manufacturing technology programs involving robotic metal welding use advanced sensor systems (such as acoustic emissions, vision, thermal, and gas flow) that can be integrated with artificial intelligence into computer software to control the process. One robotic system provides the means whereby manufacturing technology (generated by modeling and simulation) can be transferred directly to the shop floor via a computer-aided design system. Other contemporary DoD manufacturing technology investments supporting and utilizing this critical technology include utilizing robotic arms for assembling wire harnesses that have several different wire types (including twisted pairs); applying inertial measurement techniques to robotic arms; monitoring and controlling plating processes; applying a robotically controlled laser paint stripper to aircraft; and using expert systems to assist in analysis, design, and planning of factory information systems.

2. Projected Manufacturing Capabilities

DoD has contacts with other US government agencies regarding development of machine tool control technology. These contacts provide theoretical knowledge, especially in software development, which has been usefully combined with the practical applications available within DoD, and help provide a broad basis for future manufacturing capabilities and development thrusts.

For robotics and machine intelligence to achieve significant inroads into the 1990s, the following five areas require advancement:

- *Controls*: Advances are required in image analysis and understanding before true autonomous operation can be achieved. Such knowledge-based understanding can then be used to enhance autonomous navigation, threat assessment, and obstacle avoidance, to help robots become more autonomous in operation.
- *Sensors*: Sensor fusion must be advanced for better image resolution and situation awareness for autonomous operations.
- *Actuation Systems*: Advanced materials (as well as faster reacting actuators) are required, especially if robots in space become a requirement.
- *Man-Machine Interfaces*: Control of multiple robots by a single operator, simultaneous computer and human operation, reduced tele-operation, and greater autonomous operation.
- *Integration*: Integration of vision and force feedback for autonomous control, better diagnostics, and self-healing processes; integration of manipulators and dexterous end-effectors, interface standards and faster integration oftechnological advances, especially component advances into robotic systems.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

Extensive robotics/machine intelligence research is conducted by the Bureau of Mines, National Aeronautic and Space Administration (NASA), and the National Institute for Science and Technology (NIST). Work also is sponsored at universities by the National Science Foundation (NSF). While some of the efforts are DoD oriented, development of robotics/machine intelligence for use in special applications (mining operations, operation in hazardous indoor environments, and manipulator arms and appendages) are being pursued. Research in command and control, remote operation, and vision technology may be leveraged for DoD efforts.

2. R&D in the Private Sector

Machine intelligence and robotics work in the United States is robust, with new enterprises coming to market constantly. On the other hand, relatively few US companies are developing robots for commercial applications. DoD-funded research in universities includes machine planning and reasoning, knowledge acquisition by machine, knowledge representation by machine, and natural language understanding by machine. Research activity in neural networks has increased, particularly in the past three years, with most efforts still at universities but with work significantly moving toward industrial research laboratories and application groups.

About 15 to 20 start-up companies have been formed to exploit the technology in the past two years, with a market of approximately $20 million, primarily for supplying R&D efforts and focusing on computer hardware and software tools for research and prototype development. A few commercial applications have been developed, including a decision aid for processing mortgage loan applications, a device for reading handprinted amounts on checks, and an assembly line parts inspection application.

US university basic research in the area of adaptive real-time information processing and manipulator control offers significant opportunities for advances in technology leading to the implementation of a wide variety of intelligent (autonomous) and other robotic systems. The control of the dynamic performance of robotic manipulators that are programmed to follow certain desired trajectories remains a difficult and complicated task because the manipulator may be compliant in its joints and links. Therefore, progress in the design, construction, and operation of manipulator arms will be realized through the development of appropriate mathematical modeling and analysis techniques and the execution of key experimental investigations. These activities are essential to achieve a thorough understanding of the kinetics, dynamics, stability, and control of future manipulator systems made from modern lightweight materials, such as laminated composites. The university community possesses the necessary skills, knowledge, and capability to successfully accomplish these tasks.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology.

Summary Comparison--Machine Intelligence and Robotics Relative to the United States

Selected Examples	USSR	NATO Allies	Japan	Others
Development of specialized techniques for AI applications of advanced processing architectures	▨	□□□	□□□	
Practical telecontrol of military vehicles	▨	□□□	□□	
Application of advanced structural materials to robots (having high dynamic loads or required to operate in hostile environments	▨	□□□	□□□□	
Integration of smart sensors and improved actuators	▨	□□□	□□□□	
Overall[a]	▨	□□□	□□□□	□□ Finland, Israel, Sweden

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

Ongoing international research and development indicates potential international capabilities to contribute to meeting the following challenges and goals :

- Development of specialized techniques for AI applications of advanced processing architectures;
- Practical telecontrol of military vehicles;
- Application of advanced structural materials to robots having high dynamic loads or required to operate in hostile environments);
- Integration of smart sensors and improved actuators.

Principal cooperative opportunities will exist with NATO countries, especially in the area of software algorithms and image/signal processing applications, and with Japan in applications of optical neural net research.

The Soviet Union lags behind the United States significantly in machine intelligence and robotics. They do have a good theoretical understanding of the area and can show creativity in applying the technology to selected space and military applications. Soviet R&D on artificial intelligence (AI), under the auspices of the Academy of Sciences of the USSR, includes work on machine vision and machine learning. The value of machine intelligence to battlefield operations as well as to the domestic economy has been recognized by the Soviet government.

The United States has had a commanding lead in computational capabilities, but the lead is being diminished. Japan and, to a lesser extent, some of our European allies have made significant advances in the industrial application of such technology. Much of this R&D is transferable between civilian and military applications.

Japanese robotics R&D has benefitted from a 7-year joint project formed in 1983 under the Ministry of International Trade and Industry (MITI) to advance Japanese robotic R&D. The MITI project addresses sensors for sight and touch; vision control; versatile robot arms capable of both high precision and high-weight capability; efficiency motors for robots; and low-weight, high-strength materials for robots. Japan's experience in industrial robots, and its underlying technology base in associated computer science and technology, could make significant contributions to the allies' capabilities if both sides agree to cooperate in robotics technology.

The second phase (1987 to 1991) of the European Strategic Program for Research in Information Technology (ESPRIT) is addressing natural language understanding, computer vision, robotics, machine learning, computational logic, expert systems, and AI hardware/software developments.

France has emerged as a dominant force in European software and as world leader in artificial intelligence. French research is beginning to move into industrial applications. Under the European Research Coordination Agency (EUREKA) program, they are also developing capabilities for real-time threat analysis and crises management that could be, directly applicable to battle management and C^3I applications. This effort also involves Norway.

Exemplary of the capabilities of our NATO allies are the collaborative efforts between NASA and the German Aerospace Research Establishment (the DFLRV). This effort includes several robotics projects, with a stated goal of attaining a ten-fold reduction in weight over present technology. Germany is also active in research in certain aspects of military vehicle control.

The Japanese Institute of Industrial Technology and Hamamatsu Photonics have jointly developed a rudimentary optical neural computer to explore imaging processing tasks. The goal of the project is to develop "intelligent sensors." Japan has also produced what has been described as the first optical neurochip, consisting of a 32 x 32 element array implementing 32 neurons. This chip, integrated on an 8mm square (GaAs) substrate, is based on an advance in optical bonding that will allow the chip to be used more readily with other integrated circuit devices and on printed circuit boards.

Interest in neural nets within NATO countries is limited and is primarily associated with specific applications. The Netherlands and Germany have expressed an interest in neural networks, primarily in association with their work in 2-D/3-D imaging (which is, in some areas, advancing more rapidly than that of the US and Japan). The UK also has expressed an interest in the area for radar processing applications. Its Alvey program has a major effort in adaptive user interfaces that may provide benefit to future neural net applications.

Outside of NATO and Japan, interest and capabilities in neural nets appears limited to specific applications such as speech and image processing and potential application of the technology to remotely piloted vehicles (RPVs). Finland (Helsinki University of Technology) and Sweden (Royal Institute of Technology, Stockholm) have research efforts in the use of neurocomputing to pattern recognition for speech and image processing. Israel is among the world leaders in operational use of military RPVs. Opportunities for cooperation in specific niche technologies may be realized in these areas.

2. Exchange Agreements

There is a significant level of exchange activity in the diverse technologies of machine intelligence and robotics. Various NATO programs provide the US with a mechanism for exchanges of general information regarding potential application of these technologies.

The Technology Cooperation Program (TTCP) has a specific exchange in the application of AI-based aids for military operations and provides a vehicle for a range of applicable exchange activities under the variety of programs for which AI is an underlying technology (e.g., in undersea warfare, monitoring and diagnostics, signal and image processing, electronic warfare, training, guidance and control, etc.)

Each of the Services also has exchanges, primarily with NATO in areas of specific interest. These provide mechanisms ranging from general exchanges in AI research to exchanges in a variety of specific applications, including pattern recognition for smart weapons, control and operation of RPVs, implementation of smart cockpit techniques, and battlefield robotics.

5. SIMULATION AND MODELING

A. DESCRIPTION OF TECHNOLOGY

The revolutionary advances in computer technology, engineering, and basic science combine to provide dramatic new technology capabilities for DoD by enabling computer simulation and modeling of real world situations. Without involving costly testing or system prototyping, computer-based simulation and modeling (and its associated analytic simulation techniques) has many applications to design, manufacturing, diagnostics, training, wargaming, battle management, and system evaluation. Simulation and modeling will play an increasingly important role in the cost-effective training of personnel, as well as in the design of equipment that can be operated and maintained efficiently.

Physical simulation involves the development of a hardware configuration that can replicate a variety of conditions for both man and machine, such as permitting computer-controlled simulations with either man or hardware in the loop. Analytic simulation typically involves the development of computer models to evaluate procedures and processes in advance of laboratory research efforts or hardware expenditure. Examples include computer algorithms that evaluate new chemical compounds and computers programmed to dynamically demonstrate the influence of vehicle and projectile configuration on air flow patterns. One sophisticated simulation example involves the application of test data to an examination of long gun tube flexing during firing; this data will be invaluable in assessing the effect of new lightweight materials in various armor applications.

Simulation and modeling efforts influence a number of other critical technologies. For example, computational fluid dynamics, which uses analytic simulation by computer modeling, is treated in this plan as a separate critical technology because of its significance to a major industry (aerospace). Similarly, weapon target environments, sensors, data fusion, and signal processing are other critical technologies in which simulation techniques are discussed separately. The reader is referred to these separate critical technologies for more details regarding simulation and modeling efforts in each.

Simulation and modeling technology is enhanced by new developments in computer languages and concepts. For example, artificial intelligence (AI) and object-oriented programming paradigms now enable simulations based on computer objects that mimic the behavior of real objects. These techniques make complex simulations easier and more affordable.

The application of advanced techniques to very large battlefield simulations will play critical roles in increasing force effectiveness and readiness. It can also focus military system design and procurement by allowing systems to be prototyped (in simulation) and used in very large-scale simulated battlefield exercises. These simulations can also be used as a way of preparing for actual engagements.

Critical technology challenges in simulation and modeling span the improved management of complex battlefields (including camouflage and deception), training of personnel (especially in complex military environments), and improved industrial design and production (see the table below).

Critical Technology Challenges in Simulation and Modeling Technology

- Complex battle management
- Training in complex military environments
- Industrial design and production

B. PAYOFF

1. Impact on Future Weapons Systems

Simulation and modeling technology can be applied to every major DoD weapons development program to reduce design and production cost, improve performance, improve diagnostics and maintenance, assist in better and faster training of personnel, and improve command and control on the battlefield.

For example, training cost effectiveness and safety can be significantly increased by providing a sufficiently realistic interactive simulation of tanks, armored personnel carriers (APCs), portable weapons, fighter/attack aircraft, helicopters, surface combatants, and other systems. The capability for linking existing training devices worldwide will provide a level of integrated training that goes beyond the teaching of individual skills. And newly proposed systems (such as vision devices, antitank weapons, and antihelicopter weapons) can be simulated digitally so that the utility of given technical parameter requirements can be assessed before hardware is built. The use of simulation and modeling in the systems design process will enhance the operational suitability and effectiveness of all systems, whether being initially procured or being modified.

The payoff for large-scale maneuver simulation, in terms of improved combined arms training at reduced costs, has never been greater. Simulation and modeling of the combat environment involves the assessment of the effect of critical parameters (such as weapons and force effectiveness) on battlefield engagements. Simulators and models are used also to estimate human factors in this environment, including behavioral modeling of crew performance, development of computer-aided decision making aids, and design of automated controller aids for battle simulations.

Simulation and modeling concepts are applied to the assessment of sensor, observer, and processor performance to represent realistic military operational environments, ranging from digital imagery analysis to predictions of the physical effects of environmental influences (such as temperature or weather conditions) upon weapons systems and prototypes. This critical technology can have particularly heavy application in difficult operating environments such as the ocean, where environmental influences are not well understood due to the lack of available temporal and spatial information in regional or global areas. (See the discussion of Weapon Systems Environment for further details.) Model simulations will help to optimize the effectiveness of limited and costly at-sea experimental observations. Also, nuclear effects simulation is a critical element in estimating the vulnerability of our weapon systems during a nuclear weapons exchange.

In the electronic warfare (EW) area, a major payoff is the development of a coordinated force-on-force EW simulation capability that can provide assessment within the integrated combat process. The mid- to long-term payoff of this capability will be a coordinated combat management process capable of responding to immediate, mid-term, and long-term objectives. Integrated modeling techniques can be used to run individual software modules in a coordinated battle force EW simulation. The goal of these modeling and simulation efforts is to prescribe coordination procedures for combined electronic countermeasures against threats.

2. Potential Benefits to Industrial Base

DoD efforts in simulation and modeling offer many potential benefits to the US industrial base through improved training, design, manufacturing, and exploration. For example, the development of advanced environmental ocean simulation models will allow the industrial base to develop improved sensors that exploit advanced instrument technology to combine limited in situ data with existing and forecasted data. Such development can help benefit undersea or geophysical prospecting, petroleum exploration, and other applications.

DoD's industrial-related simulation efforts (designed to help produce military systems of significantly greater functionality) can also contribute to the US industrial base. Current DoD efforts in this area include developing engineering trade-off decision simulations such as the transient radiation effects on electronics (TREE) program (which simulates the "hardening" processes needed by microcircuits in a nuclear radiation environment) and diagnostics of complex systems by modeling a series of alternative situations until they match the observed failure modes.

The fields of human factors engineering and training technology are rapidly expanding and have many developments that involve simulation and modeling. A few developments relevant to the industrial base include

- Human factors engineering can be used to increase usability and decrease errors. Many human issues can impede system success if they are not studied and considered early in the development process.
- Virtual prototyping of systems, using computers and involving actual target population members in tests, can result in reduced cost of the final product and quicker arrival at the final product. Virtual prototyping can reduce the time from adoption of a weapon to assimilation of the weapon into the force in accordance with appropriate employment doctrine.
- Application of new technologies will enhance our ability to provide realistic training (to include feedback) tailored to the student's needs. These technologies include digital audio, compact disk read only memory (CD ROM), videodisc, tutoring modules, simulation-based training, holography, 3-D television, and speech recognition.
- New training strategies, primarily derived from work of cognitive psychologists, are providing insights into performance problems. These strategies are decreasing the time it takes for a novice to become an expert performer, increasing the cognitive level a student may attain in training settings, and thus increasing the positive transfer of training to the real world.

- Simultaneous engineering will integrate design and manufacturing of any product. If manufacturing aspects of the design are considered up front, product design can be altered as required before the design is frozen (thus alleviating costly downstream changes required for production). This up-front consideration of manufacturing processes allows greater emphasis on efficiency, increased quality, and reduced cost. Simultaneous engineering is a dual-use technology that can be applied to non-defense-related industrial design as well as to weapon systems design.

C. S&T PROGRAMS

1. Milestones

Milestones for this critical technology are listed in the table below.

Milestones--Simulation and Modeling

Technical Area	By 1995	By 2000	By 2005
Military simulation and modeling	• Integration of battle-field simulation into a battle management test bed to have a test and evaluation approach for new planning and decision aids, pinpointing deficiencies in exist-ing aids as the threat changes, and evalua-ting the effect of changes in our own doctrine, tactics, weapons, etc.	• Application of knowledge-based techniques for design of complex systems including large soft-ware systems and battle management simulations • Demonstration of C3I workstation • Order-of-magnitude cost reduction for training and human factors design	• Substantially improved battle management, decision aids, human factors design, and cost-reduction techniques
Industrial simulation and modeling	• Modeling performance of hypothetical designs to help make trade-off decisions for optimal design	• Diagnostics and prog-nostics by modeling alternative situations	• Substantially improved cost effectiveness, planning, and design

2. Developing the Technology

Military simulation technology constitutes a major portion of DoD's efforts in modeling and simulation technology. Current efforts include development and application of missile seeker/smart weapons simulations (used to test especially sensitive systems that would be compromised in open air tests), fiber optic helmet mounted displays for F-16 simulation, a full-scale LHX cockpit simulation (for pilot reaction to control types and different information displays), networked F-16 air intercept trainers, tank ride and motion simulation, "future" systems wargaming exercises, and full field-of-view-domes for F-16 simulation.

Battle management technology is also being pursued by DoD. Efforts include development of environmental and terrain space technology (including artificial intelligence links to environmental information), environmental data characterization development, and target recognition based on the environment. This technology will help reduce the amount of equipment and non-combatants required in the battlefield, will more effectively use resources, and will enhance survivability.

DoD also is building a national test bed simulation facility, which will simulate a wide variety of SDI-related battle management scenarios and will permit testing of newly developed computer modules. The facility will also offer limited opportunities to exercise and evaluate target acquisition and pointing and tracking hardware systems.

By using the latest advances in computer hardware and software improvements, ocean simulation modeling also is continuing to help develop technology in computational simulation and data assimilation. Simulation and modeling technology development in part relies on computer hardware and software improvements. For example, supercomputing power is critical to combine background density, temperature, sound velocity, and fluid motion structures on global and regional models. This critical technology is used to enhance warfare operations, weapons systems performance, and environmental operational analyses.

3. Utilizing the Technology

One important use of simulation and modeling technology is in training. DoD is using simulation and modeling technology to improve training capabilities in a variety of areas, including shipboard training, tactical multi-ship aircrew training, battle force wargaming, passive and active ASW sonar training, individual and team tactical decision-making training, and a wide variety of other applications. An important emerging simulation technology of benefit to all of the Services is networking. Networking will provide the capability for linking hundreds of air, surface, and ground platform simulations, and enable them to operate within a common environment data base.

DoD also is using simulation and modeling technology to develop a number of important training tools, including advanced wargaming (and troop training), links between the European Command (EUCOM) Warrior Preparation Center with individual corps headquarters, F-16 air combat training, tactical combat training, and a host of other specific training programs. Test beds also are being used to develop lower complexity, lower cost simulator design alternatives. Other training-related areas being pursued include sensor simulation, head- and eye-tracked visual simulation systems, and helmet-mounted displays.

Future modeling efforts will be used to help develop optically based (or passive) terrain-following devices; improve predictions of safe corridors following large spills of volatile hazardous materials; provide trade-off analyses for new technologies in camouflage, concealment, and deception; increase decision making for command and control; and instruct and measure performance of inexperienced personnel in the operation of key runway repair equipment under simulated wartime environments.

Total S&T funding[5] is shown in the table below.

Funding--Simulation and Modeling ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
810	210	250	230	230	230	230

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

Simulation and modeling of metalworking processes by finite element and finite difference methods is currently being carried out for forming processes (rolling, extrusion, sheetforming, etc.) such as casting, powder consolidation, and welding. The materials treated in these applications include common iron and aluminum-based alloys, superalloys, titanium, tungsten, powder materials, and composites.

Benefits to the domestic industrial base include time and cost savings in metalworking process development. Simulation permits establishment of process parameters through computerized methods, rather than through trial and error effort on actual plant equipment. In addition, simulation permits creative exploration of process alternatives in the product design stage. Thus, product design and manufacturing issues are considered simultaneously or concurrently (hence the terms, simultaneous engineering and concurrent engineering).

2. Projected Manufacturing Capabilities

Simulation and modeling of metalworking processes is a key to successful development of processes for new, hard-to-work alloys such as aluminides and rapidly solidified powders. For example, simulation, in conjunction with an experimental development program, is necessary to establish processes for forming titanium aluminides for future aerospace applications.

In EW, the magnitude and scope of the total threat demands a coordinated force-on-force EW simulation. Existing simulation capabilities are not adequate to provide a comprehensive picture of the EW coordination process. Advances in several simulation and related technology areas are required to develop and ultimately implement crucial strategies. Advances are required in the following areas: modular program development tools with advanced data structures; integration of available high-speed parallel and vector processing techniques; integration of high-speed graphics hardware and software into the workstation environment; application of expert system and related AI technology to provide

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[5] Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

simulated man-in-the-loop displays; and high-performance computer networking strategies for multiprocessing and remote EW/combatant data base coordination and access.

Overall advances in improved software development, parallel processing technology, and enhanced computer graphics are required to expand simulation and modeling capabilities.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

DoE is involved with, or is researching, future research and development efforts in the following areas:

- Virtual prototyping to enable engineers to visualize and test new components.
- Remote instruction for collective training and high cognitive level learning to replace or enhance schoolhouse learning experiences.
- High technology education, where complex realistic problem solving through collective training and learning experiences in the classroom (made possible by rapidly accessing multiple data sources).
- Simulation-based training, where students can practice high-risk scenarios with expert, immediate feedback in a cost-effective configuration.
- New weapon systems design, including human factors and training considerations via computer simulation, for the purpose of determining design effectiveness, learning constraints, and cognitive overload considerations. These new design practices also permit experimentation prior to full-scale development of the new system.

The Services also have ongoing programs related to training applications of simulation and modeling, such as oceanography applications. In EW, the Services use computer models to test virtually all systems.

Other areas in which computer modeling has significantly affected US R&D programs include weapon design and effects (nuclear, conventional, and chemical); prediction of effects of vibration, acceleration, and ionizing and non-ionizing radiation on man; and understanding interactions between low observables, materials, and geometries with electromagnetic radiation.

2. R&D in the Private Sector

Industry has a substantial investment in the development of improved real-time simulation technology for training as well as for weapon system development. All major EW systems developers produce engineering simulations prior to and during hardware design and development. These simulations are generally unique to the planned system development and not related to more generic simulation technologies being developed by the Services.

Substantial DoD-sponsored university research is underway to optimally model a wide range of processes, develop robust and efficient computer algorithms (based on the underlying theory), and employ high-performance parallel computers to exercise these algorithms. Computational science is now emerging as a discipline in most major universities. Problems being pursued include theoretical combustion, computational fluid dynamics, non-linear solid mechanics, alloy solidification, control of large flexible systems, composite materials, and non-linear optics.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Modeling and simulation are applied to a wide range of diverse applications. As the complexity and costs of hardware development increase, designers in all fields will begin to depend more heavily on modeling and simulation. The table on the following page provides a summary comparison of the United States and other nations for selected key aspects of the technology. Principal cooperative opportunities will exist with NATO countries, especially with the UK, FRG, and Canada, all of whom have substantial efforts. Ongoing international research and development indicates potential international capabilities to contribute to meeting the challenges and goals identified:

- Development of numerical techniques for modeling of non-linear processes on advanced computing architectures;
- Development and empirical validation of physical models of materials (including material reaction to extreme conditions);
- Effective application of advanced computing architectures to real-time and faster-than-real-time simulation of complex situations/environments.

Japan's capabilities in computing and industrial process control offer promising cooperative opportunities in those areas. In general, however, Japan trails the US development of empirically validated engineering data bases, specific to military systems, that are required to do effective modeling.

Many NATO countries, though lagging in certain aspects of modeling, have led the way in producing the hard data with which the models are validated and improved (e.g., the UK and its research in chemical defense). Thus, a critical interplay exists between selected modeling communities and their experimental counterparts in other countries.

Secondary opportunities for cooperation exist in niche technologies related to modeling of nuclear and solar power (Italy) and modeling of particle accelerators. In addition, the widespread effort in algorithms for parallel processing, such as that in the Netherlands (described in the section on parallel computer architectures) may contribute to advances in numerical methods in computational fluid dynamics and hydrodynamic modeling.

Many other countries are active in modeling power and transportation systems. These programs are not, however, considered leading candidates to contribute to significant advances beyond existing US capabilities.

Summary Comparison--Simulation and Modeling

Selected Examples	USSR	NATO Allies	Japan	Others
Development of numerical algorithms for modeling of non-linear processes on advanced computing architectures	▨	☐☐☐	☐☐☐	
Development and empirical validation of physical models of materials (including material reaction to extreme conditions)	▨	☐☐	☐☐☐	
Effective application of advanced computing architectures to real-time and faster-than-real-time simulation of complex situations/environments	▨▨	☐☐	☐☐☐☐	
Overall [a]	▨	☐☐☐	☐☐☐	
	[a]The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.			

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	☐☐☐☐	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	☐☐☐	capable of making major contributions
▨▨	generally lagging except in some areas	☐☐	capable of making some contributions
▨	lagging in all important aspects	☐	unlikely to have any immediate contribution

Simulation and modeling as a generic field is established worldwide in civilian applications. Primary applications are found in modeling large complex systems, most notably power (including nuclear power as an important subset), transportation, and telecommunications. These areas are of only peripheral interest at present; however, they could produce advances in software techniques for massively parallel machines that could be transferred to other problems.

Driven by the same economic considerations as the US, NATO allies are advancing computer modeling and simulation technology. With the exception of Japan, most nations lag behind the United States in their capability to manufacture high-speed scientific computers. However, there is no restriction to their purchasing these machines. Various national and multinational R&D ventures by our allies may focus on targets of opportunity that would also enhance their overall capability.

Within NATO, the UK is active in a number of areas of interest, including computational fluid dynamics and modeling of complex communications networks. A number of NATO countries have ongoing efforts relating to various aspects of modeling spacecraft control and thermal management.

Germany is using simulation to explore use of an automatic tactical fighter director with integrated fire-flight control systems for automated air-to-air combat. They are also active in simulation supporting the European Fighter Aircraft.

Canada is a world leader in dynamic training simulation and is contributing presently to the LHX combat mission simulator. France has produced six-degree-of-freedom simulations of the Puma SA 330 helicopter and the WS 13 Lynx. Specific efforts of interest include improvements in computer-generated imagery, which are reportedly adequate to simulate real-time flight dynamics with realistically textured objects in simulated day, night, and dusk conditions. The ability to do real-time dynamic imagery with detailed texture adds significantly to the training capabilities. This capability is characteristic of the state of the art in US combat mission simulation (as in the AH-64 weapons system simulator). The UK is developing and using innovative techniques for real-time display that may help to alleviate troublesome time-delay effects in aircraft simulators.

Data assimilation efforts in the United States for purposes of ocean simulation probably lag behind those of the Soviet Union. The United States maintains superiority with respect to data for purposes of modeling (prediction) and computational hardware and software for simulation and modeling.

The USSR uses simulation and modeling extensively for conducting wargaming exercises and weapons development. Although the Soviets trail the United States in computational capabilities, specifically in large-scale computers and graphics workstations, they nonetheless have a thorough understanding of the subject matter. In some applications, such as wargaming, their knowledge base of the subject matter may equal or lead that of the United States.

2. Exchange Agreements

Simulation and modeling play an integral part in the design, integration, and evaluation of most modern weapons systems. Exchange of information contributing to advances will occur through a number of mechanisms. The exchanges in physics and electronics previously noted will contribute directly to our understanding of basic phenomenology at the device level. Empirical validation of environmental models results from exchanges involving the weapons environment.

The Technology Cooperation Program (TTCP) provides mechanisms for a range of applicable exchange activities in such diverse topics as simulation of infrared scenarios, training, simulation of nuclear weapons effects, radar performance prediction, and weapon effectiveness, all of which have traditionally relied heavily upon modeling and simulation.

Each of the Services also has exchanges, primarily with NATO, in areas of specific interest. These provide mechanisms for exchanges of technology such as flight simulation, simulation of air-to-ground sensors, and modeling of flight dynamics.

6. PHOTONICS

A. DESCRIPTION OF TECHNOLOGY

Photonics encompasses the product and process technology for devices that use light (photons) and electronics (electrons) to perform functions now typically performed by electronic devices. The next 20 years will see the emergence of photonic devices in sensor, communication, and information processing systems. Defense photonics developments are aimed at achieving major improvements in tactical and strategic command, control, communications, and intelligence (C^3I) capabilities through faster, smaller, more reliable, and more survivable systems. DoD advanced technology developments in photonics include optical memories, optical signal processing, optical computer networks, optical control of phased arrays, integrated optoelectronic networks, nonlinear optical processing, and integration of electronic and photonic devices into monolithic compound semiconductor optoelectronic integrated circuits (OEIC) and laser diodes. Although fiber optics is not usually included under photonics, it is an important adjunct to it, and some important developmental aspects (e.g., ultra low-loss fiber optics) are included in this section.

Critical Technology Challenges in Photonics

- Ultra low-loss fiber optics
- High-power laser diodes and arrays
- High-speed networks with fiber optic backplane
- High-speed, low-energy optical switches
- High-performance spatial light modulators
- High-speed optical interconnects
- Opto-electronic integrated circuits
- Devices for operation in nuclear environments

During the past decade, fiber optics has greatly matured as it has gained increased importance in the commercial sector. The next decade will see similar maturation of fiber optics for use in the defense sector. Fiber optics will provide higher bandwidth capabilities to ships, aircraft, and undersea communications at lower cost than cable by factors of 10 to 100. Supercomputers and high-throughput signal processors will use optical interconnects. Ultra low-loss fluoride fibers with their theoretical loss of 10^{-3} db/km would permit transoceanic repeaterless links that could revolutionize undersea surveillance, long distance communications, and tethered vehicles such as fiber guided missiles. Fiber optical sensors will provide a new class of gyros for inertial navigation as well as acoustic and magnetic sensors for anti-submarine warfare (ASW) and commercial applications.

Laser diode arrays are being developed to scale up the usable light output from diode lasers while retaining the high efficiency (greater than 30 percent) and compactness (approximately 100 micrometer dimensions) of individual devices. Incoherent (unphased) arrays are being used as efficient pump sources for other solid state lasers; while coherent (phased) diode laser arrays have applications requiring beam focusing or propagation. For commercial applications, diode arrays may replace other less efficient, reliable, and compact types of lasers.

B. PAYOFF

1. Impact on Future Weapons Systems

Photonic computing offers the promise of order-of-magnitude improvements in processing speed resulting from the natural parallel architecture and high switching speeds of optical devices. In addition, photonic circuits eliminate many potentially troublesome connectors and increase reliability. New distributed processing architectures will exploit the absence of metal wires and related electromagnetic interference problems. Photonic devices also offer superior electromagnetic pulse (EMP) and radiation hardness. The use of OEICs would also extend weapons capabilities in the areas of automatic target recognition, state-of-health monitoring, and detection avoidance (e.g., stealth).

The processing rates required by emerging electro-optical and infrared (IR) sensors, electronic warfare, and undersea surveillance are surpassing the capabilities of currently available electronic processing (1-10 Gbit/sec). Dedicated photonic processors will soon be needed to act as sensor front ends that will preprocess the data and reduce the data rates to those compatible with current and projected electronic processors. Dedicated special-purpose photonic processors are now in use within DoD in such front-end applications.

The table below outlines the goals and payoffs associated with the DoD program in photonics:

Goals and Payoffs--Photonics

Application	Goal	Payoff
Photonic computing	• 100X increase in processing rate • 10X fewer physical hook-ups • Distributed architecture • Reduced EMI susceptibility	• Greatly improved ECCM capability for all types of sensors (IR, radar, EW, acoustic, etc.) • Enable processing of data from high density (>10^6 element) focal plane arrays, very large phased arrays, and collection systems
Ultra low-loss fiber optic cable	• Transoceanic repeatable cabling	• Large distributed ASW systems with lower costs and higher reliability
Communications	• Satellite-to-submarine communication	• Improved tactical strategic connectivity

The superiority of fiber optics over copper-based systems can be measured by information-carrying capacity (which is 10,000 times greater for optical systems), energy loss in signal transmission (100 times lower), error rate (10 times lower), greatly reduced size and weight, and by its resistance to electromagnetic interference, nuclear environments, and other harsh environments. Future developments in semiconductor lasers promise diode-pumped lasers, and modulators promise still greater improvements in data rate capacity and link margin.

Ultra low-loss fiber optics is of great importance to DoD in a number of critical military capabilities:

- Wide area communications
- Wide area surveillance
- Undersea and tactical missile guidance (low-cost, target, and aimpoint selection)
- Remote surveillance and tele-operated weapons platforms (removing requirement for personnel to enter high-threat areas).

This technology consists of optical fibers fabricated with zirconium fluoride (ZrF) glasses. These glasses are the lowest scatter material ever produced and represent a major advance in glass chemistry. This technology enables such systems as large aperture, high-gain, acoustic arrays (thousands of acoustic sensors interconnected over tens of kilometers), and long-range command-guided anti-ship missiles. Continuous integration of electronic processors and controllers with fiber optical devices, nuclear hardening, improved interconnects, switches and multiplexers, higher power, frequency tunable optical sources, and high bandwidth sensitive detectors are important elements of this technology.

Incoherent diode laser arrays operating in a long-pulse mode are finding use as pump sources for Neodymium: yttrium aluminum garnet (Nd:Yag) lasers. In this application, their ruggedness, reliability, and energy efficiency greatly exceeds that of conventional flashlamp pump sources. Diode-pumped solid-state lasers have demonstrated 10 times higher efficiency and 100 times better reliability than flashlamp-pumped laser systems. Incoherent arrays are also being used for direct optical ignition of pyrotechnics (e.g., explosive bolts on rockets) through optical fibers. These lasers require modest (1 watt) power levels and are expected to be a high-volume application because they significantly enhance safety and EMP-resistance. Other applications for ignition of energetic materials in conventional and nuclear weapons are likely to follow.

Coherent diode laser arrays have applications for optical radar, satellite communications, directed energy, and undersea ASW. In-phase operation of an array directly increases the amount of power that can be transmitted and focused on target. In addition, by controlling the optical phase of each of the emitting diodes, electronic beam steering has been demonstrated at very low power levels.

Future DoD missions are expected to have computational requirements that exceed the performance of future digital electronic computers and signal processors. Digital optical computers have the potential to meet these future requirements.

2. Potential Benefits to Industrial Base

Photonics R&D should significantly affect the industrial base in a number of areas of high-speed computing, through the development of components such as high-speed lasers, detectors, interconnect media, and signal routing and control elements. DoD relies heavily on commercial development in areas such as high-speed local area networks

(LANs) and transoceanic cabling. Fiber optics R&D being pursued by DoD for specialized applications will affect relatively limited areas (e.g., intrusion resistant fiber optic links).

Diode-pumped solid-state lasers offer the potential of more powerful lasers with greater reliability and lower cost (inexpensive enough to warrant replacement rather than repair). Diode laser arrays are expected to have numerous industrial applications, replacing older types of laser. Applications include laser printers, read/write optical disks, and illumination for robot vision. In manufacturing, diode arrays are expected to find widespread use in applications requiring power levels of 1 to 100 watts. These include machining (cutting, drilling) and surface-treating (conditioning, texturing, heat-treating) of a variety of materials. The small size and relaxed power and cooling requirements of diode arrays allow direct point-of-use positioning, eliminating the need for beam transmission optics.

C. S&T PROGRAMS

1. Milestones

Milestones--Photonics

Technical Area	By 1995	By 2000	By 2005
Cryptography	• Limited intrusion detection secure communications without encryption to 50 MBPS	• Secure optical communications without encryption	
Photonic devices	• 10x improvement in spatial light modulators and dynamic range • 10x increase in input/output bottlenecks • 14-inch tactical optical disk with 6-GB data capability • 10^{12} read-write-erase optical disk--1.6 gbps throughout • 500 MOPS signal processing • 200 MHz ELINT recorder/processor • Optical interconnect for computer	• 14-inch jukebox tactical optical disk with 120-GB data capability • 1 GOPS signal processing • High accuracy/high density light-weight phased array atennas • 1 GHz ELINT recorder/processor • Medium density/high accuracy L-, S-, and X-band optically controlled phased arrays • Integrated photonic/electronic/microwave devices	• On-chip, massive optical interconnects • Integrated optical signal processor for spectrum analysis • Opto-electronic heterodyne receiver for laser radar
Sensor applications	• Demonstrate multiplexed fiber optic sensor system	• Demonstrate distributed fiber optic sensor (10x the number of acoustic channels used in 1990)	• All optical surveillance and communications systems performing simultaneous operations with no individual function performance penalty • Distributed fiber optic sensor in full-scale development
Local area networks	• 2 Gbit/sec LAN	• 5 Gbit/sec LAN	• 1[illegible] Gbit/sec LAN
Undersea cabling		• Demonstration of 20 GHz bandwidth	
Fiber optic gyro (FOG)	• Demonstration of fiber optic gyro of ESG accuracy	• Demonstration of FOG incorporating ultra low-loss fibers (10x increase in accuracy over ESG)	• Demonstration of FOG with 100x increase over ESG

(Continued)

Milestones--Photonics (Continued)

Technical Area	By 1995	By 2000	By 2005
Diode lasers		• 100W, CW, coherent laser • 10x reduction in cost of diodes and arrays (coherent, area) • Individually addressable diode laser arrays	• 1-D and 2-D arrays with low threshold (<1 ma) and high differential quantum efficiency • Low current threshold, vertically emitting diodes • 100x reduction in the cost of diode lasers and arrays

2. Developing the Technology

DoD has a broad-based R&D program in photonics including photonic signal processing, microwave/ millimeter wave photonic processing, optical networks, ultra low-loss fiber optics, and photonic materials. The DoD program includes developments of semiconductor lasers, optical modulators, and switches as well as integrated optical designs incorporating such devices. Ultra low-loss fiber optic technology is being pursued by DoD for incorporation in engineering developments by the mid- to late-1990s. Efforts include developing a rugged, non-kinking fiber optic cable for use in fiber optic guided weapon applications and the inclusion of photonic sensors for electromagnetic fields generated in nuclear environments.

Recent advances in diode lasers indicate that this technology has matured to a point where it is usable for laser pumping of compact solid-state lasers. While implementation for systems is technically feasible, costs are excessive. Accordingly, DoD has initiated a tri-service laser diode array manufacturing technology program. The goal of this 36-month, 3-phase program is to develop the technology and manufacturing techniques to produce laser diode bars for solid-state laser pumping as standardized low cost components.

Major research is also ongoing in materials, crystal growth, device fabrication, and their application to the integration of electronic and photonic devices. Programs include the development of laser arrays (including surface emitting arrays) as well as the integration of lasers and other optical components with electronics on chip.

S&T funding[6] for this critical technology is shown below.

Funding--Photonics ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
560	100	110	110	115	120	120

6 Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

3. Utilizing the Technology

A number of other ongoing DoD activities are related to exploiting the new opportunities associated with photonics technology. The Navy is pursuing a diode laser/solid-state laser approach to underwater applications including submarine laser communications, tactical airborne laser communications, and mine detection and bathymetry. In addition, DoD is developing diode-pumped lasers for jamming and/or damaging sensors.

DoE efforts are underway to utilize laser diode arrays in weapon systems for high-power trigger signal generation, power transmission via an all-optical interface, direct optical detonation, range and imaging optical radar systems, and optical correlation.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

US manufacturing capabilities in photonics can best be assessed by considering the following four application areas.

a. Telecommunications

The $100 billion annual market in photonics is primarily in commercial applications, and the key product in this area is fiber optic cable. While US industry is meeting market demands, current manufactured products do not meet all of the DoD requirements for ruggedness over temperature range and higher performance. Currently, a DoD-unique manufacturing programs involves fiber optics cabling for transmit-receive terminals. This is the first program nearing production to use fiber optics in a secure communication system (performance levels are for 12 mega-bytes per second at 1.5 km).

b. Information Processing

Approximately half of the demand for photonics in information processing is for commercial applications. Optics technology is utilized in digital input/output interconnections.

c. Optical Storage and Display

This market is still dominated by magnetic disc storage. However, present manufacturing capability for optical standard discs is 5.25 inches, one of three types of optical discs currently being manufactured (others are erasable optical and write once read many (WORM)). US industry trails Japanese in cost and quality of current manufactured optical discs. Overall growth rates of more than 15 percent per year are predicted in the optical storage and display industry during the next 5 years.

d. Optical Sensors

Fiber optic sensors are the major commercial product in this area, and the current market is about $5 billion annually. Component quality and reliability (i.e., super luminescent diode/laser diodes) are currently provided by foreign sources. They require long lead times and are very costly. Military applications such as focal plane arrays are entering manufacturing arenas. Extensive commercial R&D is underway.

2. Projected Manufacturing Capabilities

The US industrial base capability reflects utilization demand, including fiber optics for telecommunications, digital information processing, and optical storage. The US industrial base generally is not expanding its technology emphasis because of limited market demand. However, technologies are maturing in lasers (laser jamming systems, etc.), optical gyros (several companies are testing preproduction fiber gyros), and fiber optic connections, and newer approaches to information processing (digital computations) should receive manufacturing technology funding to address producibility issues. Ultra low-loss fiber optics will require new manufacturing processes to remove impurities. Other contemporary DoD manufacturing technology investments supporting and utilizing this critical technology are aimed at reducing the costs of fiber optically controlled missile components.

The development of advanced optoelectronic integrated circuits will require significant strengthening of this country's industrial base in compound semiconductor manufacturing. Only a limited number of commercial companies are capable of manufacturing devices.

The manufacture of high-power diode arrays is a very specialized technology due to critical requirements for device growth, processing, and mounting. These devices are fabricated from gallium arsenide (GaAs), and little specialized equipment for volume processing is currently available. In addition, the fabrication of diode lasers requires mirror fabrication equipment. Current technology for the fabrication of diode arrays is labor intensive, but efforts are underway to reduce unit cost for incoherent arrays through volume production and standardization.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

A number of government agencies besides DoD support R&D in photonics. The DoE has contributed in two specific areas: computer modeling and heat sinking and cooling. The computer codes used to model phase conjugation processes are expanded versions of codes developed for the inertial confinement fusion program. DoE's laser program has also focused on issues of array heat sinking, bonding, and cooling.

Diode array development in the national laboratories is concentrated on the development and qualification of arrays for weapons applications plus fundamental research aimed at understanding the coupling and phasing of the individual diodes in an array and the development of advanced coherent arrays (on-chip injection locking for control and beam steering).

NASA has provided partial funding and technical expertise from NASA-Langley on three ongoing diode-pumped solid-state laser demonstration projects.

2. R&D in the Private Sector

Extensive industrial R&D efforts in photonics technology are underway, particularly in the telecommunications industry. Fiber optics are essential to the telecommunication industry, and fiber sensors are being employed in medical, process control, and safety monitoring applications, to name a few.

US research in single mode fiber optic systems is driven by increased demand for bandwidth. For example, in high-definition television, even with data compression, data transfer rates of 135 Mb/sec may be needed. A number of experimental projects are underway to introduce fiber optics in providing commercial information and television service to homes. One of these will provide the initial test of microwave frequency (2 Gb/s) subcarrier multiplexing.

Because of the potential for space-based lasers with these approaches or with the closely related diode-pumped solid-state laser approaches, a number of companies are sponsoring substantial IR&D activity in diode lasers, which complements the government investments.

Several universities have established consortia with industry and/or government partners to pursue work in optical computing, including the Optical Circuitry Cooperative at the University of Arizona's Optical Sciences Center, the University of Southern California's Center for Photonic Technology, the University of Alabama at Huntsville's Center for Applied Optics, and the Center for Optoelectronic Computing Systems at the University of Colorado. Several universities, notably the University of Illinois and the University of New Mexico, have made excellent progress in high efficiency, quantum well laser devices. In addition, a number of universities have excellent programs in optoelectronics including the fabrication and study of 1-D diode arrays. These include California Institute of Technology, University of Illinois, University of California at Santa Barbara, University of New Mexico, Cornell University, and the University of North Carolina.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Ultra low-loss (less than 0.001 db/km) fibers
- Research in photonics, bistable devices, and other specific components
- Increased volume production of high-power laser diode arrays
- Development of optical interconnects, including fiber optic backplanes

- Greater than 2 Gbit local area networks
- Radiation-hardened components
- Application of fiber optics to improved inertial sensors.

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology. The United States and Japan share a worldwide lead in this technology. NATO allies have significant efforts that, in aggregate, have the potential to rival either the United States or Japan. The commercial and military potential of photonics are such that most of the industrialized countries of the world are making a significant national commitment to develop photonics.

Principal cooperative opportunities will exist with NATO and Japan, especially in applications of compound semiconductor superlattices and organic nonlinear optical materials. Cooperative opportunities also exist with NATO countries in niche technologies relating to associated components required to fully exploit low-loss fiber capabilities and to exploit fiber optics technology in harsh environments.

The United States has a lead in the area of the laser diode array technology. Use of narrow linewidth diode lasers and tunable solid-state laser sources have allowed US researchers to optimize solid-state laser compositions for diode pumping. The Soviet Union lags behind in this area, largely due to the lack of vapor phase growth technology, which essential for obtaining high-quality material for the fabrication of low-threshold, high-efficiency laser diode arrays. The Soviet Union also trails the United States in the modeling of arrays.

NATO activity involves government, industry, and universities. The combined Euromarket planned for 1992 is expected to have an integrating effect on work now underway in Europe on advanced optoelectronic technology, quantum wells and superlattices, materials, focal plane arrays, optical interconnections, and switching, as well as on the application of these technologies to remote sensing, imaging, and industrial processes. France's previous dominance in the area of photonics will be shared with the UK, FRG, and Sweden, with much active research in laser diodes as well as bistable and high-speed optical switching. Other basic research is being carried out with complex GaAs/GaAlAs and InGaAs/P structures. The UK, FRG, and France are also active in the field of quantum wells and superlattices for optical and integrated optical devices.

One of the largest optical computing programs in Europe, the European Joint Optical Bistability Project, involves eight universities and institutes in the UK, Belgium, FRG, Italy, and France. In France, research is being conducted on liquid-crystal light components at the University of Paris (Orsay). Thompson-CSF also is pursuing a major effort on optical processing. In West Germany, Erlangen University is investigating parallel logic, optical cross-bar switches, spatial filtering, and logical operations using polarized light. The University of Duisberg has built a very fast optical multiplier and broadcast bus, which will support communications between modules in a computer. The Fraunhofer Institute has developed an optical local area network.

Summary Comparison--Photonics

Selected Examples	USSR	NATO Allies	Japan	Others
Ultra low-loss (less than 0.001 db/km) fibers	▨▨	□□	□□□	□ Various
Research in photonics, bistable devices, other specific components	▨▨ [a]	□□□	□□□	□ China
Increased volume production of high-power laser diode arrays	▨▨	□□□	□□□□	
Development of optical interconnects, including fiber optic backplanes	▨	□□	□□□	□ Brazil
Greater than 2 Gbit LAN	▨	□□□	□□□□	
Radiation-hardened components	▨▨	□□	□□	
Application of fiber optics to improved inertial sensors	▨▨	□□	□□	
Overall [b]	▨▨	□□	□□□□	□ Various

[a] The Soviets are reported to have a world lead in spatial light modulation.
[b] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

Japan is pursuing research and development in all areas of optical processing, with government, industry, and universities all heavily involved. The key government participant is the Ministry of International Trade and Industry. Most of the large electronics companies in Japan have made a commitment to this effort. A special trade organization, the Opto-electronic Industry and Technology Development Association was founded in 1980 to coordinate industrial activity, foster cooperation, and encourage standardization. Universities in Japan are performing much of the basic materials research on which the technology development is so dependent. In 1984, the Japan Society of Applied Physics established a research body called the Optical Computer Group, which illustrates how seriously Japan is taking the field of optical computing. The group has members from universities, government laboratories, and private companies.

Japan leads the world in transferring R&D in fiber optic technologies to various commercial applications and has manufactured considerable amounts of low-loss optical fiber (e.g., less than 0.1 dB/km). The Japanese have a major investment in both fiber optics and the ancillary photonic devices needed to use them effectively. The UK, France, and the FRG also have technically advanced efforts in fiber optics. These countries can all produce low-loss optical fibers but may have difficulty in producing the fibers in large quantities.

A number of countries are actively pursuing related topics. In 1988, the Japanese (Fujitsu) demonstrated the first broadband optical integrated services digital network (ISDN). NEC has demonstrated an experimental optoelectronic receiver, using reported development of high-mismatch epitaxy of GaAs and InP, capable of 2-GB/second modulation rates. A number of Japanese firms and British Telecom are pursuing coherent communication techniques that are advertised as having near-term potential to extend transmission capabilities to 4-GB/second. If realized, these cababilities would be significant advances. The UK is also researching special fibers (high-birefringence, polarization-preserving) for sensor applications.

Other countries with significant development efforts in photonics include Sweden, Switzerland, the Netherlands, Israel, China, and Korea.

2. Exchange Agreements

There is a significant level of exchange activity in all areas of photonics, including integrated optics, optical materials, fiber optics, and related components. The NATO Defense Research Group (DRG) programs in physics and electronics and optical and IR technologies provide mechanisms for exchange of fundamental scientific information. The Technology Cooperation Program (TTCP) sponsors a group focused on the military application of optical fibers and components. The TTCP also provides a mechanism for exchange of information on basic materials and specific applications. Each of the Services also has exchanges, which cover a spectrum of activities ranging from basic research in optical science with France and the UK, application of the technology to optical processing (principally with France) and a program with the FRG for specific application of the technology to the integration of main battle tank electrical, electronic, and optronic systems.

7. SENSITIVE RADARS

A. DESCRIPTION OF TECHNOLOGY

Continued reduction in target observables will significantly reduce the range of existing US surveillance, tracking, and target classification capabilities. Sensitive radars (such as wideband radar, lower frequency radar with anti-jam and low-probability-of-intercept capabilities, bistatic radar, laser radar, and advanced over-the-horizon (OTH) radar) will be required to handle future advanced low observable threats.

Radars sensitive across a wide frequency spectrum force an enemy to reduce the radar-observable characteristics of their systems across many frequency bands and force an increase in robustness and sensitivity of their own radars. Bistatic radar (which separates the radar transmitter and receiver--possibly by hundreds of miles) eliminates radar emissions from the receiving platform, making the platform harder to detect and enhancing survivability. Impulse radars also may provide important counter-stealth capabilities, thus the term "sensitive radars" refers to radars that not only detect conventional targets but also exploit special target characteristics or use special techniques such as wideband, multispectral, dual-polarization, multistatic, doppler, and other advanced methods for extracting additional valuable information.

Critical Technology Challenges for Sensitive Radar Technology

- Wideband radar
- Laser radar
- Sensors for non-cooperative identification
- Miniature synthetic aperture radars

Non-cooperative targets (i.e. targets that do not overtly identify themselves or that disguise themselves electronically) challenge radar technology not only in low observability. For example, simply detecting a noncooperative or noncommunicative (possibly neutral) target is not sufficient basis for action. The target must also be classified (is it aircraft or missile, tanker or destroyer?), recognized (is it friend, foe,or neutral; armed or unarmed?), and identified (is it the same target seen in another place or at another time?) before appropriate actions can be taken. Obtaining this additional information requires future microwave, millimeter-wave, or laser radars that possess enhanced sensitivities. A number of high-resolution radar technologies may provide such capabilities. These include inverse synthetic aperture radars (ISAR), millimeter-wave (MMW) radars, impulse radars, and high-range-resolution (HRR) radars.

Coherent laser radars also represent direct analogs of microwave radars in the optical frequency range. They provide advantages of bandwidth, physical size reduction (e.g., in antennas), and higher resolution. But laser radars at the same time possess disadvantages that accrue from scattering and absorption characteristics of the shorter wavelengths; these disadvantages result in attenuation of the coherent laser radar beam and the manifestation of undesirable speckle patterns (arising from target roughness and atmospheric turbulence).

B. PAYOFF

1. Impact on Future Weapon Systems

Sensitive radar technology is a major factor in providing a technological edge to US forces by enhancing detection, localization, classification, identification, and tracking capabilities. Radar sensor technology, at both RF and laser frequencies, will remain a major factor in future warfare. It is crucial that techniques be developed to counter ongoing threat efforts to reduce the observable radar signatures of weapon platforms.

Ultra-wideband radars (operating at lower frequencies) offer a potential to detect such stealthy targets and will provide simpler, lower cost, more reliable, lighter weight radars, which can perform many functions of high-resolution radars. Further, the dynamics and range of future engagements (including nuclear environments), will force a greater reliance on radars for real-time, noncooperative target recognition (NCTR). High-resolution RF sensors will allow for detection of targets hidden in foliage and also will provide an important capability that is not now available. Integrated sensor approaches will allow for multiple functions and collection of multiple target signatures, which are not now available.

Laser radar technology will have its greatest impact in the areas of navigation for cruise missiles, helicopters and robotic vehicles; detection and discrimination of strategic targets; recognition and identification of tactical targets with low false alarm rates; and standoff chemical sensing. Laser radar imagery also is expected to play a key role in future smart weapons systems. Proposed uses of laser radar include, but are not limited to, cruise missile guidance, target recognition and homing for smart weapons systems, aimpoint refinement, and fusing.

Goals and Payoffs--Sensitive Radars

Sensor Type	Goal	Payoff
Radar (monostatic, multistatic, impulse)	• Counter 1000x reduction in observables • Counter threat reduction of RF emissions from threats • Counter threat counter-measures	• Counter emerging stealth threat • Improved ECCM capabilities and operation in severe environments (high clutter, operation on board high acceleration missiles)
Concealed target detection sensors (high-resolution/ imaging radar)	• Enhanced wide area search and detection of targets in clutter • Low frequency synthetic aperture radar (SAR) with wide angle/polarization diversity	• Long-range detection of mobile military targets under all weather conditions • Reliable detection of concealed/camouflaged military targets • Concealed target recognition
Laser radar	• High-resolution, large-volume surveillance for strategic defense • Effective discrimination between RV threats and non-threat objects • 3-D characterization of concealed tactical targets	• Rapid, accurate hand-off to SDI weapon fire control • RV discrimination against full range of penetration aids • 3-D sensor for tactical automatic target recognition (ATR) system
Noncooperative target recognition	• Effective identification of low observables targets in near real time • Real-time, noncooperative identification in complex tactical environment	• Enable use of beyond-visual-range weapons • Fratricide reduction

2. Potential Benefits to Industrial Base

Eye-safe, low-power laser radars are being investigated for a variety of commercial applications, including robotics, automated manufacturing processes, and speed determination (e.g., police radar). As the cost and availability of solid-state and injection laser radars are improved, substantially broader usage is expected. The Ti:sapphire tunable laser radar possesses enormous potential for environmental monitoring, including remote assessment of compliance. Use of tunable Ti:sapphire laser radar and high-speed chemometric analysis of spectroscopic signatures can also play a major role in the drug war through the remote identification of chemical effluents associated with drug factories and the remote location of marijuana fields by the multispectral analysis of reflectivity and fluorescence signatures.

C. S&T PROGRAMS

1. Milestones

Milestones--Sensitive Radars

Technical Area	By 1995	By 2000	By 2005
Radar (monostatic, bistatic, multistatic)	• Fly multistatic radar on UAV • Multiband radar concepts • High dynamic range component measurement • Technology feasibility of impulse radar	• Demonstrate conformal radar • Demonstrate ultra-wideband receiver/ transmitter • Determine effectiveness of anti-stealth radar concepts	• Demonstrate advanced anti-stealth radar concepts
Advanced OTH radar (AOTH)	• Determine limiting environmental factor	• Test-bed measurements to confirm performance	• FSED for AOTH in place
Laser radar	• Demonstration of capability for strategic defense	• Define capability of laser radar for tactical applications	• Demonstrate compact laser radar for ground troops
Concealed target detection sensor (high-resolution/imaging radar)	• Design/develop wide area search sensor • Develop automatic detection algorithms • Flight test capability	• Initiate FSED program	
NCTR radar	• Develop data base and algorithms for NCTR radar • Field demonstration of 2-D imaging radar	• Initiate FSED on NCTR radar	

2. Developing the Technology

DoD research and development programs are demonstrating multispectral technologies for detection, tracking, and non-cooperative classification of advanced airborne threats in the future countermeasures environment. Programs are underway for UHF/L-band radars, dual-band radars, high frequency (HF) over-the-horizon radars, airborne bistatic radar, and the associated sensor fusion. DoD S&T programs, both completed and ongoing, have assessed designs for several airborne and shipborne radars. Ongoing programs address radar components, sensor concepts and demonstrations, bistatic radar approaches, associated algorithms and processing schemes, and high-range resolution and imaging radar system developments for NCTR.

Modular low-probability of intercept (LPI) radars and multistatic radars are being developed for unmanned airborne platforms or elevated platform payloads. The DoD radar program is also addressing countermeasures to radiation missiles. The results of this work are being used in the multirole, survivable radar for air defense. The multisensor target acquisition system program is an effort to integrate a millimeter-wave radar with foward-looking infrared (FLIR) and other electro-optical sensors to achieve highly reliable, all-weather target detection and recognition.

Wide-area search and cueing sensor techniques are being developed to enable reliable detection of targets situated in various kinds of tree cover, foliage or camouflage. Such a sensor must be capable of operation in all weather and in all seasons. It will require the development of a low-frequency synthetic-aperture-radar employing wide angle and polarization diversity and must provide the capability of high signal-to-noise (detection) with low false alarms.

DoD has an aggressive technology development effort for radar techniques for target identification and raid assessment. Ongoing programs cover ultra high-range resolution, range-only radar; ISAR and other imaging radars; and the fusion of radar data with other sensor data. DoD also has an effort to develop compact radar antennas and anti-jam (AJ) LPI techniques for HF/VHF/UHF frequencies.

The Strategic Defense Initiative (SDI) laser radar program is developing space-based technologies for fire control, discrimination, and active imaging of strategic threat objects. The technologies being developed include high-power laser transmitters, detectors, beam steering concepts, modulators, amplifiers, signal processing techniques, and related analytic tools for fire control, discrimination, and imaging applications. DoD R&D activity also includes development of new prototype laser sources and sensors including laser rangefinders, imaging laser radars, and laser vibration sensors. Research work is ongoing for new or improved solid-state laser sources is underway.

Total S&T funding[7] for this critical technology is shown below.

Funding--Sensitive Radars ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
880	110	130	140	150	150	150

3. Utilizing the Technology

DoD programs that presently utilize or may (in the near future) utilize emerging sensitive radar technologies include the following:

- Obstacle Avoidance System (OASYS)--The objective is to provide helicopters with a compact, light-weight, wire and obstacle avoidance sensor to prevent accidental strikes, which cause losses of equipment and personnel.

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7 Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

- Air Defense Target Identification--Laser vibration sensing is one of a number of candidate technologies being investigated as candidate approaches for non-cooperative, positive identification of air targets.
- Infrared Lidar for Stand-Off Chemical Agent Sensing--an IR lidar may be effective as a remote sensor for discriminating among chemical agents.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

Phased array technology is being transferred into manufacturing, but application has been primarily to ground-based, low-volume systems. Manufacturing capability for the active element modules can be characterized as mainly manual operations with some simple semiautomatic processes such as wire bonding and component attachment. Considering that an airborne application may require more than 2,000 modules per radar, current manual operations do not meet anticipated production requirements.

Advanced radar sensors currently under development generally employ a phased-array antenna. The antenna may be built from a large number of relatively low-power active elements or from a smaller number of high-power radiation sources that provide power to many transmit elements. The former technique employs solid-state transmit/receive (T/R) modules and has been demonstrated in L, S, C, and X-band. L, S, and C-band modules are available but need to be made smaller and lighter for space applications. X-band modules have been designed, evaluated, and fabricated manually at low volumes and, therefore, are very expensive for airborne applications.

Two manufacturing concerns exist for phased-array antennas that depend on a few high-power radiation sources: traveling wave tubes (TWT) and ferrite phase shifters. The TWT industrial base is weak and heavily dependent on military orders. TWTs have high failure rates and frequently require long lead times to purchase. Some TWTs for use in military systems are now being purchased from Europe. The manufacturing base for ferrite phase shifters is also rather limited. This technology is costly and results in delayed deliveries. Solid-state phase shifters are an alternative but may not handle the power required. In addition to electronics manufacturing issues, the dimensional tolerances specified for large phased array antennas create a significant manufacturing problem. Finally, there are few facilities to test large phased-array antennas.

2. Projected Manufacturing Capabilities

A DoD manufacturing technology program aimed at reducing the cost and increasing the producibility of X-band transmit/receive (T/R) modules for airborne applications is underway. This program addresses all aspects of the manufacturing process, including test, and should make significant reductions in module cost. The DoD has similar programs underway for L and C-band modules.

DoD has recently awarded manufacturing technology contracts to investigate the manufacturing cost and producibility of T/R modules. The program entails the design of a module for manufacturability, utilization of new cost-effective materials, and innovative assembly and test techniques. Emphasis is on statistical process control, modeling and simulation, automation equipment technologies, and factory system integration. The goals of the program are to achieve a $400 module at production rates of 1,000 per day.

Millimeter-wave technology is probably sufficiently advanced to allow fabrication of a radar, but additional efforts are required to develop the manufacturing base. Laser radars must still be classified as R&D systems, but manufacturing technology programs for them will be required when the technology is ready for transition to a manufacturing environment.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

Laser radars and associated technology are being developed by NASA for atmospheric sensing and remote sensing from space, by the Environmental Protection Agency (EPA) for pollution monitoring, and by the Federal Aviation Administration (FAA) for windshear detection and velocimetry. NASA is currently developing laser remote sensing techniques using tunable laser sources. Picosecond laser technology is also being developed for satellite-based imaging of topological features with millimeter-scale resolution. These capabilities will, however, reside in separate instrumentation packages.

2. R&D in the Private Sector

Significant industrial R&D has occurred on high-efficiency diode laser pumping of solid-state lasers. Synthetic aperture radar and multispectral sensors are being pursued for commercial use in earth resource mapping.

University research efforts related to sensitive radars center on materials research, electromagnetic propagation and phenomenology studies, and basic physics work. These efforts are often performed independently from specific sensitive radar programs.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified.

- Development of extremely wideband radar, wideband microwave sources. and antennas
- Active element arrays, including conformal arrays
- Beam steering, application of coherent laser diodes, laser radar
- Development of improved techniques for microwave and millimeter-wave radiometry.

In general, the United States is the world leader in all aspects of sensitive radar technology. The table below provides a summary comparison of US and other nations for selected key aspects of the technology. Principal cooperative opportunities will exist with NATO countries, especially with the FRG and the UK.

Summary Comparison--Passive Sensors

Selected Examples	USSR	NATO Allies	Japan	Others
Development of extremely wideband radar, wideband microwave sources, and antennas	▨	□□	□□	
Beam steering, application of coherent laser diodes, laser radar	▨▨	□□	□□□	□□[a] Sweden
Active element arrays conformal antennas	▨	□□	□□□	
Overall[b]	▨	□□	□□□	□□ Sweden

[a] While not predominant in any key aspect of this technology, Sweden has reported some interesting research in target characterization with high-resolution laser radar.

[b] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

The Soviet Union has maintained an active program in laser remote sensing for a number of years. The Soviet approach to laser radar technology has been advanced and innovative, encompassing such concepts as nonlinear laser radars based on coherent anti-Stokes Raman spectroscopy and optical parametric oscillator technologies. Presentations by Soviet researchers have even suggested the use of nonlinear photorefractive materials for high-resolution remote imaging. Even though Soviet thinking on laser radar technology appears advanced, their relevant technology base is well behind current US capabilities.

The UK, France, and the FRG report ongoing efforts in synthetic aperture radar and inverse synthetic aperture radar technology, as well as basic programs in techniques for distinguishing targets of interest in high-clutter environments. There is significant R&D in the UK on coherent radars and in synthetic aperture radar imaging at the FRG Aerospace Research and Development Center. British Aerospace has developed a smart mortar projectile based on sensitive radar techniques.

Both Japan and the UK have microwave device and subassembly technologies with the potential to contribute to development of active element arrays, while the United States has long enjoyed a lead in system integration. Recently, however, France has demonstrated a state-of-the-art capability in advanced techniques for antenna testing.

The UK has a significant effort in laser radar technology; Canada, France, and West Germany also have strong ongoing programs. Small programs in the use of laser radars for remote sensing reside in all of the major European countries, with Germany and Sweden currently being the most active. France and Germany are actively pursuing joint investigation of the use of laser radar for helicopter detection and recognition.

Both France and Norway are studying the use of radar imaging techniques against surface targets (ships, armor, etc.). Sweden appears to have a significant effort covering a wide range of topics relating directly to NCTR. Of particular note is a program involving the characterization of aircraft target features with a CO_2 laser radar.

Japan possesses a large data base of practical knowledge on laser radar capabilities for remote sensing applications. The only area in which Japan has a clear disadvantage is in the development of the high-power laser sources needed for long-range target imaging and identification.

2. Exchange Agreements

Radar is the subject of a high level of exchange at all levels. The NATO Defense Research Group (DRG) programs in long-range research for air defense and in electronic warfare concepts and technology provide mechanisms for exchanges of fundamental information relating to radar requirements and design. The program in physics and electronics also provides a mechanism for supporting advances in materials and components critical to implementation of active conformal arrays. The Technololgy Cooperation Program (TTCP) has a large number of radar-specific exchanges that provide mechanisms applicable exchange activities in generic radar system design, signal processing, and radar performance modeling, as in specific areas such as electronically agile radar, OTH radars, and radar sensors for RPVs.

Each of the Services also has a number of exchanges with NATO and other friendly nations in areas of specific interest. These provide a mechanism for general exchanges in radar, as well as in specific applications such as ground- and satellite-battlefield surveillance (including an exchange with Germany in phased arrays). Examples of areas of exchange underlying technologies include millimeter and microwave components (France), computational antenna design techniques (Spain), and radar target characterization (UK).

8. PASSIVE SENSORS

A. DESCRIPTION OF TECHNOLOGY

Passive sensors (i.e., sensors that do not emit radiation in order to find targets, but instead merely "listen" for them) will be increasingly important to counter future enemy reductions in observable characteristics across many frequency bands. Passive sensors include electronic support measures (ESM), infrared/electro-optical sensors, acoustic sensors, and multi-spectral sensors.

Critical Technology Challenges for Passive Sensor Technology

- Passive threat warning sensors
- Microwave/millimeter-wave radiometry
- Passive coherent radar
- Advanced thermal imagers
- Infrared search and track sensors
- Infrared focal plane arrays
- Compact antennas
- Superconducting sensors
- Fiber optic sensors
- Large, volumetric acoustic arrays
- Sensor integration/correlation

A number of important passive sensor microwave and millimeter-wave techniques are being developed by DoD. New techniques are extending the capabilities of threat warning receivers and ESM to enable broader coverage of the electromagnetic spectrum. Microwave radiometry continues to evolve for imaging of noncooperative targets. Passive sensor techniques for use with coherent radar (bistatic, noncooperative radars) may provide important radar capabilities without the vulnerabilities associated with conventional radars.

Infrared (IR), visible, ultraviolet, and x-ray passive sensors include advanced thermal imagers, IR search and track systems, and a range of novel IR focal plane array approaches. Mercury-cadmium-telluride (HgCdTe or HCT) technology is being developed for operation at long-wave IR (LWIR) wavelengths, yet barriers remain in the manufacture of large focal plane arrays. Doped silicon technology (that operates at temperatures less than 20 degrees Kelvin and is sensitive in the medium- and long-wave IR bands) is being developed for single and dual color imaging systems. Silicon impurity band conduction (IBC) detectors also are now emerging as viable. Efforts are underway to improve their sensitivity, radiation hardness, and ease of production.

Alternate materials for LWIR detectors are needed because of the manufacturing problems with HgCdTe and the severe cooling requirements for IBC silicon detectors. Detector materials are also needed due to manufacturing problems with platinum silicide

(PtSi) arrays. Recent breakthroughs in advanced IR sensors (based on InAsSb strained-layer superlattices) for staring photovoltaic arrays and quantum well structures (based on GaAs/AlGaAs) for photoconductive detectors make them viable candidates for manufacturing development to fill needs for LWIR sensors.

Military applications requiring compact antennas and arrays are numerous, ranging from ground-based communications antennas to conformal antennas on the surface of aircraft, missiles, and projectiles.

Passive acoustic arrays have many technological aspects Ever larger and more sophisticated arrays are being developed to increase array gain and obtain increased resolution for interference suppression. Conformal arrays are also being developed that allow for the sensor array to be built into the skin of the platform. All aspects of passive acoustic arrays need investigation: sensor technology, array and system architecture, signal processing technology, processing algorithms, system architecture, and system components.

Recent advances in superconductivity also offer a significant opportunity for new sensors. Superconducting devices are being developed for use as electromagnetic sensors across a broad spectrum from extremely low frequency (ELF) through infrared frequencies. Superconducting quantum interference devices (SQUID) are being developed for magnetic anomaly detection of submarines. Superconductivity is also being applied to extremely sensitive microwave and millimeter wave receivers. Superconductivity will allow the development of super directive compact antennas. Superconductivity is being applied to develop gyroscopes, inertial sensors, and gravimeters. (See the description of superconductivity for additional details of its use in sensors.)

Fiber optic sensors are being developed in connection with the measurement of electromagnetic quantities during weapon system development and certification testing. An emerging area of this technology is the development of a fiber optic chemical sensor. These remote sensors would have wide-ranging applications.

B. PAYOFF

1. Impact on Future Weapon Systems

Passive sensing is a critical adjunct to US anti-stealth efforts. The effective exploitation of passive sensors enhances US system survivability even in high-threat nuclear environments. Multi-band passive IR and electro-optical sensors can reduce the sensitivity of existing sensors to environmental and target signature variations. Integrated sensor approaches will allow for multiple functions and collection of multiple target signatures. Such capabilities are not now available.

US Navy control of surface and subsurface ocean areas has been put at risk by rapid Soviet progress in submarine quieting and other submarine acoustic technologies. Advanced acoustic sensors are needed to counter this threat and regain an advantage over quieter submarines. A major effort exists in the development of large-aperture, high-gain passive acoustic arrays to enable long-range detection of quieter submarines.

Fiber optic sensors also support major improvements in anti-submarine warfare (ASW) surveillance as well as provide the basis for autonomous underwater vehicle guidance. Future acoustic towed arrays from surface ships and submarines require at least 10 times the number of acoustic channels in either multi-line or extra-long arrays. Fiber optic acoustic sensor arrays appear to offer the best approach for this application.

Fiber optic sensors embedded in structures will provide continuous coverage of critical internal variables (like stress and temperature) to evaluate structural performance. Further, fiber optical gyros offer order-of-magnitude lower cost for weapon and autonomous vehicle guidance. Fiber gyros are small, all solid state with no moving parts, rugged, and reliable. An order-of-magnitude improvement in accuracy over state-of-the-art gyros may be possible with fiber gyros that incorporate ultra low-loss fibers.

Goals and Payoffs--Passive Sensors

Sensor Type	Goal	Payoff
EO/IR sensors (including focal plane arrays)	• 1000x more detectors per focal plane • Much greater producibility • High resistance diode detector arrays for high sensitivity • Low-noise signal processing on detector chips • Nondestructive in-process testing for affordability	• Enable passive sensor operation with very high resolution and good ECCM capabilities (e.g., for use in ship air defense) • Crucial to overall US edge in satellite surveillance (real-time, high-resolution capability) • Crucial to tactical surveillance and weapon systems
Compact antennas	• Enable small high gain antennas to operate at lower RF frequencies • Lower profile • Reduced size and weight	• RF missile guidance systems that are effective against stealthy targets • Greater mobility • Stealth
Superconducting sensors	• Low-noise magnetic sensor	• Expanded range for magnetic detection of submarines
Fiber optic sensors	• Ultra-sensitive acoustic, magnetic, chemical, temperature, and other sensors	• Extended detection range • Lower cost, light-weight, highly reliable sensors
Multispectral sensors	• Techniques and data base to exploit signatures across spectrum	• Counter stealth and ECM • Exploit full range of target observables
Sensor fusion	• 10x improvement in tracking accuracy • Effective target identification	• Greatly improved capability to engage targets
Microwave radiometry	• Tactical images	• Enable passive sensor operation at moderate resolutions in poor weather
Diagnostic sensors	• 10x less downtime	• Improved weapon system availability

2. Potential Benefits to Industrial Base

The effect of the IR focal plane array work on the industrial base is minimal as the technology has primarily DoD applications. Advanced cooled focal plane arrays will fulfill only highly specialized tasks in industry, drug enforcement, fire fighting, medicine, and commerce and are not likely to be used in general applications. Room temperature IR detection technology, however, has great potential for commercial application (e.g., automobile driving in adverse weather conditions if inexpensive arrays can be produced).

The sensor/seeker technology critical to weapon system developments has only a few possible, though important, applications in the commercial marketplace. Space-based imaging sensors have proven successful for earth and space science applications related to the environment and its changing nature. Information on pollutants and their propagation will provide significant help in improving and maintaining the atmosphere and earth. Manufacturing efficiencies could also result from such data.

Sensors to be utilized for spacecraft station keeping purposes, such as communication and weather satellites, and earth surveillance should also provide a limited market for commercial exploitation.

Concepts developed or enhanced as part of the defense industrial base, such as computer-integrated manufacturing, flexible computer-integrated manufacturing, design by experiment, and concurrent engineering are directly exportable to the commercial market. Applications of these concepts are critical to the attempts of the US defense or industrial markets to maintain or regain global competitive advantage.

Sensors in many forms are pervasive as diagnostic tools--high-temperature electronic sensors on engines, room-temperature sensors in built-in test equipment on manufactured products, or substituting for eyes of robots on the factory floor.

C. S&T PROGRAMS

1. Milestones

Milestones--Passive Sensors

Technical Area	By 1995	By 2000	By 2005
Multispectral passive sensors microwave/ millimeter-wave	• Demonstrate passive coherent radar concept • Ultra wideband passive microwave sensors • Pre-detection single frequency band sensor fusion capability	• Multi-color IR sensors displayed • Fusion of multiple wideband sensors	
EO/IR sensors	• Enhanced MWIR InSb and platinum silicide producibility • Demonstrate VLWIR silicon IBC technology • Radiation hardness demonstration • LWIR HCT producibility demonstration • Five-year space qualified cooler • Demonstrate advanced thermal imager	• Strained layer superlattice IR detectors in production • GaAs and germanium multiplexers in production • Monolithic supercomputing LWIR with readout electronics • Demonstrate advanced IRST (with FPA) • SOS multiplexer	• Manufacturing LWIR FPAs based on GaAs/AlGaAs or InAsSb (300K operating temperature)
Compact antennas	• Determine field performance prototype antenna	• Develop design methodology for antenna	
Microwave radiometry	• Laboratory demonstration of sensor for tactical applications	• Anti-ship sensor demonstration • Anti-tank sensor demonstration	• Demonstration of advanced capability against land targets in clutter
Superconducting sensors	• Define potential for IR sensor	• Demonstrate magnetometer	• Demonstrate IR sensor
Fiber optic sensors		• Demonstrate multiphased fiber optic sensor	• Demonstrate distributed fiber optic sensor
Sensor integration	• Tracking demonstration	• Capability to predict sensor fusion performance	• Fusion of multiple wideband sensors

2. Developing the Technology

DoD has a substantial technology base effort in passive IR, visible, ultraviolet, and x-ray sensors to improve battlefield capabilities, improve target acquisition performance, and in particular, improve sensitivity in adverse weather. Emerging LWIR systems feature 64x64 2-mil pixel arrays, with 128x128, 2-mil pixel systems anticipated in the near future. Mid-wave sensors have been produced with 488x640 array sizes using platinum silicide material. IR sensors are being developed for space applications, for both strategic and air defense. DoD is also working to improve the sensitivity of visible, ultraviolet, and x-ray detectors. In addition, DoD is investing in small, reliable coolers, particularly for space applications.

Infrared search and track sensor technology for long-range search, target acquisition, and track is being pursued for fleet air defense, high-altitude unmanned autonomous vehicles, ship self defense, and aircraft target detection. This DoD program also includes an IR background measurements and analysis program. Background discrimination remains a significant problem for such infrared sensors.

DoD has maintained a broadbased program for wide area surveillance of air targets using various space-based IR sensors. The current emphasis is on development of scanning IR sensor techniques and the associated clutter rejection algorithms.

DoD efforts in multispectral sensing are incorporating a number of passive sensor techniques and demonstrating techniques for integration of passive RF and IR sensor inputs. A number of other multisensor efforts are pursuing similar technologies in other applications.

The Navy is actively pursuing passive acoustic sensor array technologies to counter the Soviet submarine quieting program. This program in acoustic arrays includes high-gain conformal acoustic arrays, broadband arrays, and ocean bottom sensors. These programs rely heavily on advanced signal processing techniques.

Environmental processes are particularly important for understanding the capabilities of new sensors. The increasing sophistication of sensors raises the importance of clutter discrimination to overall sensor performance. Ongoing R&D programs are addressing oceanic and atmospheric effects on sensors on a variety of spatial-temporal scales. These modeling and data collection efforts are being used as the basis for sensor and algorithm design as well as for characterizing the sensor performance.

Total S&T funding[8] for this critical technology is shown below:

Funding--Passive Sensors ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
1,900	460	420	420	430	440	440

3. Utilizing the Technology

DoD programs that presently or may in the near future utilize emerging passive sensor technologies include the use of infrared focal plane arrays as an element in the development of

- Advanced electro-optical air defense system
- Multisensor target acquisition demonstrator
- Deep fire smart munitions
- Families of advanced small arms
- Increased soldier survivability
- Rotorcraft Pilots' Associate
- Heavy Force Modernization.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

Infrared focal plane arrays (IRPFAs) form the basis for many of our future passive sensors. Current efforts are concentrating on the mid (MWIR), long (LWIR), and very long wavelength regions of the spectrum. The Air Force manufacturing technology program has two MWIR HCT detector array programs that will demonstrate a two million pixel per year manufacturing capability and reduce the cost of the arrays by a factor of ten or more. The total cost of these programs is $29 million over a four-year period, and the programs will be completed in April 1991. These programs are directed toward strategic applications. The Defense Advanced Research Projects Agency (DARPA) IRFPA program is establishing a manufacturing capability for MWIR PtSi arrays and LWIR HCT arrays for tactical applications. The Strategic Defense Initiative Office (SDIO) is establishing two pilot lines for production of extrinsic silicon detector arrays for very long wavelength applications.

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8 Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

Sputter deposition facilities providing ultra-clean vacuum and special tooling to permit proper resonator film growth are needed for a range of DoD sensor types. Cooled infrared focal plane arrays fabricated in mercury-cadmium-telluride are not, nor are they likely to become, commercial items. Their manufacture requires specialized processing similar to, but not identical with, silicon and III-V semiconductor processing. The high quality material and specialized processing required, therefore, will need special manufacturing support from DoD. The arrays developed with silicides use many standard silicon process technologies, and thus will be partially supported by the substantial commercial base.

2. Projected Manufacturing Capabilities

Ongoing HCT IRFPA programs will provide the basic manufacturing skills required for application of that technology; however, there may be other manufacturing programs required to address system specific requirements for increased uniformity and detectivity for the detector arrays. In-process and acceptance testing is a major cost driver for HCT IRFPAs. Methods for decreasing the time and increasing the throughput for IRFPA testing are required. Although the DARPA IRFPA programs will solve the LWIR array manufacturing problems, they are specifically addressing tactical applications. Additional work may be required to establish a HCT LWIR manufacturing capability for the lower background strategic applications. It is anticipated that the superlattice technology will be ready to transition from an R&D to a manufacturing environment in the 1995 to 2000 time frame.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

The DoD efforts in developing passive IR technology are coordinated with both NASA and industry. There are a small number of research efforts at universities and at the national laboratories on superconducting sensors (both RF and IR) and strained superlattice detectors. The only area in which current non-DoD funding is significant in supporting related research is in materials development for superconductors. The NASA efforts in cryogenic cooling for spaceborne sensors are similar to those of DoD.

2. R&D in the Private Sector

University research on passive infrared sensors has generally addressed basic issues in material growth, surface physics, and advanced device concepts such as single and multiple quantum wells and superlattices. Processing technology has been almost exclusively supported at industrial laboratories. Continued and expanded support of the establishment of II-VI processing technology at selected university research centers is an important element of the development of critical, high-yield processing technology. University work has shown high temperature superconductors at 240K which will improve the sensitivity of bolometric arrays at thermoelectric temperatures and which, therefore, could be significant for future infrared imaging. University efforts effecting passive sensor technology development include R&D in superconducting sensors (both RF and IR) and strained superlattice detectors. Such programs are often funded through DoD or DoE. Other university work that can indirectly contribute to passive sensor technology includes fundamental studies in optoelectronic materials and basic physics research and phenomenology. These efforts often are performed independently from a specific sensor thrust.

Small Business Innovative Research (SBIR) programs are being undertaken to acquire knowledge critical to the achievement of higher yields in the production of HgCdTe epitaxy for infrared focal plane arrays (IRFPAs). These programs will provide insight into the role of precipitates, dislocations, and subgrain structure on the suitability of epitaxial material for IR detectors and their impact on yield and performance degradation. Studies are being conducted to determine the mechanisms by which defects form, the temperature of formation, and their behavior during subsequent annealing.

Further SBIR work supporting uncooled technology is directed at improving the temperature coefficient of resistance of bolometric materials. An advance in ferroelectric materials is also being investigated that has application to uncooled detectors.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified.

- Material processing and fabrication of large-scale IR focal plane arrays
- Full militarization of SQUID sensors
- Fiber optic sensor systems.

French research in optical/IR detectors is considered state of the art in many respects and is considered a viable source of exchanges for second-generation FLIRs.

Opportunities for cooperation in niche technologies may be realized in Japan, whose solid-state technology could clearly make significant contributions. The Japanese, despite their limited experience in military sensors, are beginning to contend in second-generation IR imaging and advanced EO sensors, with the advanced development of a 1000x1000 element Schottkey-barrier device. While such devices have inherently lower quantum efficiencies than competing compound semiconductor detectors, they offer significant offsetting improvements in terms of uniformity of response and output signal to noise.

Japanese expertise in optical fibers and related components also provides an excellent base for advancing technology of fiber optic sensor system (FOSS). Their lack of direct experience in military FOSS is offset by the strength of the basic technology infrastructure. Other countries identified as having significant programs are Israel and Sweden. Their programs contribute to novel applications and device technology.

Summary Comparison--Passive Sensors

Selected Examples	USSR	NATO Allies	Japan	Others
Material processing and fabrication of large-scale detector arrays	▨▨	□□□□	□□□	□ Israel
Full militarization of SQUID sensors	▨▨	□□	□□	
FOSS	▨▨	□□	□□□	
Overall [a]	▨▨	□□	□□□	□ Israel

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

European countries have continued their development of HCT detectors. Literature from Poland indicates continued progress in improved performance. The Soviets are believed to have developed a FLIR using a linear HCT detector array for use on tanks and possibly helicopters. There is little evidence, however, of mass production and deployment of FLIR systems to date.

The Soviets are pursuing Stirling cycle coolers for space applications; however, they lag domestic development in terms of long lifetime and high reliability. They have published results of innovative concepts utilizing pulse tube refrigerators and appear to be far ahead of the United States in this technology.

Work in Poland includes vapor phase growth of HCT, but with the effort in focal plane arrays considerably behind the United States. The Soviets are believed to have some linear photoconductive HCT arrays in the field.

The Soviet Union and the Eastern European countries have not reported on the uncooled detectors although interest in these devices probably exists.

Silicon thin-film impurity band conduction (IBC) technology was discovered in the United States and is export controlled. As a result, silicon research by our allies is primarily on bulk materials. There are reports that German industry is working on silicon IBC devices.

NATO allies have expertise in second-generation focal plane array fabrication. The British have developed 128x128 switched multiplexer arrays imaging in the 8-12 micron region. The French have developed a producible liquid phase epitaxial technology from a tellurium melt which provides arrays imaging in the 8-12 micron region. The long wavelength cut-off is limited by the charge handling capacity of the silicon charge coupled device readout processor. Arrays of 288x4 and 64x64 have been made and are being acquired by the DoD for evaluation. The total amount of R&D in HCT materials in Europe is small compared to ongoing US efforts.

The British have developed pyroelectric materials for use in infrared sensors. British imaging systems are available commercially. However, the resolution and sensitivity of the US systems is superior and has better applicability to military requirements. The Australians have a low resolution bolometric system used with smart processing for perimeter surveillance and again the sensitivity is considerably below that obtained in the United States.

Japan has ongoing work in vapor phase growth of HCT but is lagging in the application to focal plane arrays. They have significant work in platinum silicide, and 512x512 detector arrays are commercially available but are expensive.

Research and development of HCT is conducted by the British, French, and Israelis; and the FRG is presently producing the linear HCT detector array used in the US modular FLIR. Again, the R&D efforts are minimal compared to the US effort due to the difference in need for strategic sensors for national defense. The British are well behind in production and test capability but are very competitive in passivation (encapsulation) techniques and understanding of HCT detectors. The French have developed a process to fabricate HCT detectors that is competitive with the United States. This process has been recently licensed to a US company. The Japanese have reported IR detection using superconducting materials; however, it does not appear to be a concerted effort.

Only the British have a space-qualified cryocooler. This Stirling cooler has been life tested for a five-year equivalent period and is currently being produced. This technology is not yet available to the United States. Philips (Netherlands) and the FRG have been identified as sources of closed/split-Stirling cycle coolers for IR detectors. Israel has advertised a cooler similar to that currently used on the TOW night sight, but details of its performance and reliability are not known. The Italians are aggressively working on magnetic refrigerators and have tested a no-moving-parts cooler.

The Japanese are ahead of the United States in the area of multi-band-capable components using dissimilar compound semiconductor materials (e.g., GaAs with InP).

2. Exchange Agreements

There is a high level of exchange activity in virtually all aspects of all types of passive sensors. The NATO Defense Research Group (DRG) Long-Term Scientific Studies and Long-Range Research Related to Air Defense, Optics and Infrared Technologies, and Electronic Warfare Concepts and Technology all will provide a mechanism for some level of exchange of fundamental requirements and scientific information in passive electromagnetic, battlefield acoustic, and electro-optical/IR sensors. The DRG on identification of submarines is directly applicable to passive ASW towed arrays.

The TTCP also provides mechanisms for a range of applicable exchange activities. Specific topics under TTCP include IR and EO sensors, undersea warfare and sonar, EW signal processing and radar emitter identification (passive intercept techniques).

Each of the Services also has a significant number of exchanges, primarily with NATO and other friendly nations in the topics listed under the TTCP as well as passive acoustic and seismic detection for ground systems and counter-intrusion detection. The Services also have exchanges in specific application of passive sensor technology, such as space-based IR surveillance and airborne ASW acoustics. In addition to these directly related programs the Services have exchanges in such topics as sensor techniques for limited visibility, radar signature and target characteristics, optical (including IR) propagation, and millimeter-wave measurement techniques.

9. SIGNAL PROCESSING

A. DESCRIPTION OF TECHNOLOGY

Signal processing is the technology used for extracting the relevant information from signals received by sensors that allows a human operator to make decisions. Because of improved signal processing, decision-making processes increasingly are being automated. Such automation of human functions in the highly dynamic and hostile environment of future warfare will enable standoff weapon engagement capabilities not otherwise possible. In many cases, signal processing technology has increased the trustworthiness of the extracted information to the point that a machine can be relied on to make consistent decisions.

Signal processing technology combines techniques for using advanced electronic devices, algorithms, and computer architectures that are developed to meet the increasing numbers of threats, counter stealth, automate operations and avoid overloading human operators, and process more complex signals from advanced sensors.

Critical Technology Challenges in Signal Processing

- Matched filter techniques
- Model-based approaches
- Artificial neural networks
- Hybrid optical-digital techniques
- Signal processing for phased arrays
- Algorithm development
- Training set development

In the area of devices, the signal processing emphasis lies in developing techniques that support super-throughput devices that satisfy analog and digital processing needs, including high-speed sensor deterministic front ends, adaptive filtering techniques, and very flexible data processing filtering techniques. The various processing needs require different device design and packaging schemes to meet individual weapon system requirements. (The DoD Very High Speed Integrated Circuits (VHSIC) program, now completed, provided high-speed, high throughput signal processing for support of requirements for military systems in the 1990s and beyond.) Signal processing algorithm development is directed to create processing methods that will meet future high-threat environments (e.g., clutter, chaff, and electronic warfare). Signal processing technology also encompasses the integration of multiple processing algorithms and devices into a coherent function while providing fault tolerance and ease of software integration. This technology also includes techniques used for multi-sensor integration associated with advanced platforms and smart weapons.

Most conventional signal processing systems continue to adhere to a classical sequence of preprocessing, filtering, detection, segmentation, property measurement, classification, and tracking. A variety of approaches to signal processing has been developed. These critical technology challenges include

- *Correlation or matched filter techniques*: Correlation classification involves taking the cross correlation between representations in one-, two-, or three-dimensional space. The correlations must be taken for all target aspect angles, sizes, and positions of interest in the surveillance field. The correlation process tends to be computationally intense and is therefore well suited to multi-dimensional optical correlators. Model-based classification is a recent variant of correlation classification.
- *Adaptive multi-dimensional processing*: This approach takes advantage of the multi-domain sensor observables (spatial, temporal, and polarization) in the target environment by providing full adaptation in all these domains. The approach is implemented through multiple parallel multi-dimensional filtering banks that realize matched filter performance (versus "best fit" performance) of a single filter. This adaptive approach allows the implementation of high throughput VHSIC devices in deterministic systolic and highly flexible architectures (e.g., in reduced instruction set computers (RISC)) to optimally handle the processing problem. This approach allows for multi-spectral data association and correlation between sensor types to significantly enhance detection, tracking, and identification.
- *Model-based approaches*: This involves reduction of target images to only those features significant to the correlation process used--for example, using only line segment orientations and their relative locations. These features are then extracted and passed to a knowledge-engineered process of logical operations which identifies one of a set of target classes. With this technique, it is also necessary to accommodate the wide variations in target aspect angle, although the process can be made invariant to apparent target size.
- *Neural networks*: The implementation of this approach to signal processing differs fundamentally from the other approaches in that signal processing is carried out in a distributed multilayer array of nonlinear elements that are interconnected by adjustable linear networks whose weights can be altered through training on known target images. Neural network processors are fundamentally different from classical Von Neumann digital processors in that they have no central processing memories or software.

Effective phased arrays (e.g., radar and acoustic) rely heavily on signal processing technology. The focus of DoD R&D in phased arrays is on providing the basis for complex computations in near real-time for phased array systems. Of particular interest are cases involving non-Gaussian interference and nonstationary noise. Adaptive processors are being investigated to deal with distributed jammers and other distributed interfering sources, such as shipping in the case of acoustic systems. Large aperture array systems are being investigated to increase array gain and obtain increased resolution for interference suppression. Conformal arrays, which allow for the sensor to be built into the hull or skin of the platform, are also being pursued . Phased microwave array radars eliminate the need for physically controlling the radar beam by means of parabolic reflectors. Similarly, phase-controlled laser arrays eliminate the need for mechanical means of steering the laser beam.

B. PAYOFF

1. Impact on Future Weapon Systems

Application of signal processing technology to conventional weapon systems offers significant advantages, such as relieving operator workload and increasing kill probability. Signal processing can automate wide area surveillance, target search, classification, identification, tracking, and aimpoint selection, as well as provide survivable communications. Although fully automatic target recognition (ATR) is not expected in the near term, immediate opportunities for automatic target cueing (ATC) exist, in areas such as undersea targeting, small land-attack standoff weapon guidance, over-the-horizon targeting, airborne multiple-target fire control, anti-ship and other air-to-surface missiles, and assistance in finding strategic relocatable targets.

The table on the following page summarizes the current state of the art in signal processing technology as well as its long-term potential.

The aerodynamics of flight requires that airborne antennas be located within the structural envelope of the aircraft, for example, in bubble-like radomes transparent to microwave radiation. These radomes must be robust and able to operate in trans- and post-nuclear environments. A logical extension of technology would be to develop radomes and antennas that conform to the skin structure of the aircraft, thus resulting in conformal arrays. By embedding the transmit/receive electronics into the conformal array and adding health (status) sensing, a "smart skin" is produced. Signal processing advances are critical to providing such a capability.

A major threat to DoD radars is the ability of enemy units to detect their emissions and to target them with anti-radiation missiles. To counter this threat, DoD is developing low-probability-of-intercept (LPI) phased-array radars (quiet radars) and communications systems that use one or more very narrow beams, and that possess very low sidelobes and steerable sidelobe nulls. The latter allows the system to automatically tune out jamming or to deny a signal to a known enemy receiver. (Signal processing is the foundation of this technology.)

Ever-changing electronic countermeasures (ECM), stealthy atmospheric targets, and dense signal environments threaten and challenge weapon systems. The challenge is to counter the threat and provide real-time high-confidence reports on the target's position and motion vectors, and supply information needed for target recognition. This can be achieved only through the application of multi-domain (spatial, polarization, and temporal) signal processing methods to extract target information such as radio frequency (RF) signature and communication messages in the complex electronic warfare (EW) environment. Electronically scanned phased arrays are utilized to give accurate azimuthal and elevation position and allow nulling of EW threats, while maintaining low sidelobe performance. The cornerstones of this technology thrust are multi-domain algorithms, high-fidelity devices, and processing architectures. The major thrusts in algorithm development include advanced spatial beamform/nulling techniques, waveform/processing methods to enhance detection and discrimination capabilities, and multi-spectral fusion to enhance detection and identification of targets and tracks and hence overall report confidence to users. These processing methods will be applied to multi-mode and multi-frequency monostatic sensors, multi-static sensors, and various electronic counter-countermeasures (ECCM) waveform designs.

Goals and Payoffs--Signal Processing

Targets	Current State of the Art	Long-Term Potential
Fixed high-value ground targets (bridges, hangars)	• Ready for engineering development (laser and IR techniques)	• More robust techniques
Ships and submarines at sea or in harbors	• Technology available (SAR/ISAR) for advanced development	• Near automatic recognition capability
Moving targets in moderate/low clutter (aircraft against clear sky)	• Technology potentially available using noncooperative target recognition techniques (e.g., IR, conventional or MMW radar)	• Move to more automation of recognition function
Advanced atmospheric target in high clutter and EW environment	• Limited capability exists	• Fusion of multispectral sensors required with high-resolution processing
Unobscured fixed land targets in benign back-grounds (tank in desert)	• Within state of the art for cueing (IR) • Ready for advanced technology demonstration	• More robust cueing and eventually automatic recognition • Multisensor approaches and laser radar
Moving targets in cluttered background and under the influence of obscurants, weather, and countermeasures	• Still a subject of research or early exploratory development at the testing and signature collection stage	• Not likely to achieve full automation • Pilot will remain in the loop • Improve robustness to environ-mental conditions
Fixed land targets in highly cluttered back-grounds/partially obscured (tank in bushes or trees)	• Still a subject of research or early exploratory development	• Success uncertain • Technology will evolve with this as a future goal
Secure and survivable communication	• Modest individual standalone capabilities exist	• Robust survivable integrated networks
Strategic relocatable targets	• Promising techniques emerging (SAR/ISAR)	• Limited capability possible • Capability against obscured targets and countermeasures much less certain
Quiet submarines	• High-gain, volumetric arrays under evaluation	• Capability against quiet targets
Moving targets in space on earth clutter	• Detection with low-sensitivity sensors	• Automated detection, acquisition, track, and kill assessment

With advances in onboard signal and data processors, future space systems will be able to withstand both the natural and enhanced radiation environments for extended periods of time. These more reliable space systems will result in less maintenance and lower life cycle costs. In addition, surveillance platforms in space will be capable of detecting, acquiring, and tracking incoming ballistic missiles in their boost phase and handing over their state vectors to orbiting interceptor and mid-course platforms, which in turn will continue to track and then destroy the incoming ballistic missiles. This entire scenario will be achievable in real time with the advent of space-based signal processing. With space-based signal processing, significant data reduction can occur in space, thereby minimizing the amount of ground processing and support equipment necessary to support such a system.

Space missions impose requirements on electronics not found in terrestrial applications. The ionizing radiation environment of space damages or destroys semiconductor devices in electronic circuits. Cosmic rays in space can change the data stored in computer memories. The detonation of a nuclear device introduces radiation hazards to which electronics are very vulnerable: transient radiation pulses, high fluxes of gamma rays and x-rays, and high intensities of neutrons. Unless special materials and techniques are used in the electronics design and incorporated in the manufacturing process, these natural and man-induced hazards can degrade, disrupt, and even destroy electronic circuits. Yet spacecraft weight restrictions force computer designers to minimize power consumption to keep the power system small, leading to low-voltage thresholds that are more susceptible to charged particles impinging from space. Components must be reliable and capable of being repaired or reconfigured remotely. The issues of low power, long life, reliability, radiation-hardness, and high performance may compromise the design of spacecraft electronics in ways not necessary for commercial electronic systems. DoD is developing advanced, radiation-hardened, very large-scale integration (VLSI) technology necessary to overcome the issues associated with operation in space, for performing real-time signal and data processing on board strategic defense system (SDS) spacecraft and interceptors.

US Navy control of surface and subsurface ocean areas has been put at risk by rapid Soviet progress in submarine quieting and other submarine acoustic technologies. New acoustic array capabilities are being developed for the SSN-21 program as well as for undersea surveillance systems. These programs rely heavily on advanced signal processing for adaptive beam forming, matched-filter processing, and target recognition.

Artificial neural network technology, a critical aspect of signal processing, is expected to provide an edge as a force multiplier in smart weapon systems, surveillance systems, and command/control systems. The ability of neural networks to perform pattern recognition could allow the recognition and classification of acoustic emanations from quiet submarines, as well as the detection of torpedo launches. In electronic warfare support measures and electronic warfare, neural networks may allow the accurate sorting and classification of emitter types in peacetime and wartime modes. The lethality of missile systems may be improved by using neural networks that can recognize real targets from false targets such as flares. Successful voice and speech recognition systems using neural networks could reduce significantly the workload of fighter pilots. Autonomously guided missiles could use neural network technology to recognize the threat and alter its course accordingly and to recognize the target area automatically and with high accuracy. Some neural networks that can detect and recognize temporal sequences will be invaluable as decision aids in command and control systems.

2. Potential Benefits to Industrial Base

Signal processing technology is also applicable to the industrial base. Signal processors are being developed to recognize handwritten characters for automatic zip code recognition systems and for handwritten data entry to computer systems. Speaker-independent voice and speech recognition systems are being developed. Seismic signal processing by means of neural networks for the detection of natural resources (oil and gas) and possibly earthquakes will be extremely useful if proved feasible. A number of emerging biomedical applications of signal processing include computerized axial tomography (CAT) scanners and electrocardiogram (ECG) analysis. Neurocomputers, which are used to emulate many of the neural network models, are creating a new industry to solve problems that conventional computers have not successfully or efficiently solved.

The successful use of VHSIC technology and products in the marketplace has continued in a wide variety of technical areas. A broadening of the industrial base for VHSIC capability has occurred as more manufacturers are providing 1.0 to 1.25 micron technology on certified production lines. The number of companies developing design automation tools specifically targeted for use with the VHSIC Hardware Description Language (VHDL) also has increased sharply. These efforts represent a significant diffusion of VHSIC-developed technology into the electronics sector of the US economy.

The radiation-hardened signal processing components have a number of industrial applications. Their high total dose immunity makes them excellent candidates for use in nuclear reactor robotics. In addition, commercial space missions, such as planetary orbiting probes and space stations, can achieve improved fault tolerant operation and extended mission duration due to the ability of radiation-hardened components to withstand high levels of space radiation.

C. S&T PROGRAMS

1. Milestones

Milestones--Signal Processing

Technical Area	By 1995	By 2000	By 2005
Algorithms	• Advanced real-time model-based approaches combined with statistical techniques • Model-based algorithms, high-fidelity target models • Increased feedback • Improved scene context • Improved robustness to environment • Effect of atmosphere and weather	• Supervised and adaptive nonsupervised hardwired neutral network algorithms • Enhanced multi-level sensor fusion • Multiple feedback between algorithms spaces • Complex scene understanding	• Advanced perception algorithms • Adaptive environmental response capability
Model development	• High-fidelity target, low-fidelity background models for radar, electro-optical imaging sensors • Single-sensor approaches • Performance extrapolation to different environments	• High-fidelity target, background, atmosphere, and sensor models for complete system prediction analysis • Mitigation or adaptation to environment	• Addition of high countermeasures environment capability
Applications	• Signal processing for airborne, multi-mode conformal array	• Signal processing for airborne, multi-function systems • Signal processing for long-range active sonar	• Smart skins technology aircraft • Signal processing for large-aperture, high-gain passive acoustic array

2. Developing the Technology

The DoD program develops signature data bases, algorithms, hardware, and tests for components and systems. Specific program goals typically are guided by the intended application (e.g., much of the Army effort is focused on LHX requirements for target acquisition) but encompass other more generic aspects as well.

A central element of DoD's ATR program is the development of a real time ATR processor. The multi-function target acquisition processor (MTAP) is a real-time signal processing tool to promote ATR science representing advances in algorithms and electronics. The efforts include knowledge-based adaptation, algorithm enhancement, building a copy of MTAP, and maintaining the MTAP. The current program is also developing a miniaturized high-throughput processor for terminal-guided munitions application. The algorithm development thrust consists of multi-sensor feature-level fusion processing, a laser vibration algorithm investigation, and model-based algorithm development.

Enhanced testing capabilities are being developed with an electronic terrain board used to simulate passive infrared (IR) signatures of military targets in realistic backgrounds. These synthetic methods are being expanded to include a variety of active and passive sensors (e.g., IR sensors, laser radar, and millimeter-wave sensors), with emphasis on validating their realism. DoD is developing standard, reproducible test and evaluation methods for signal processors that are acceptable to industry. The focus is on the establishment of a test facility in which sensors and signal processors will be tested as integrated systems. This facility includes the three-dimensional terrain board, electronic terrain board, and the automated sensor/processor center (AUTO-SPEC) computer hardware and software. It is capable of testing and evaluating the end-to-end sensor-to-signal processor combination, as well as the intermediate stages of the processor. Signature and data collection efforts are also underway to acquire tactically relevant imagery for algorithm development and evaluation.

DoD has numerous signal processing technology programs aimed at automatic targeting of undersea targets. Current systems are man-intensive and require the integration of data from many sources. Proliferation of threats has increased the volume of data to be processed, and automation of the target recognition process is needed. ATR technology applicable to over-the-horizon, autonomous anti-ship missiles is also being investigated. A program for air targets is being conducted that share generic technology with specific anti-surface weapons developments.

DoD's image processing language (image algebra) attempts to provide a mathematical foundation for digital image processing operations, to standardize algorithm notation, and to demonstrate algebraic capabilities and algorithm optimization techniques. The model-based imagery sensor target exploitation and recognition program is developing multi-sensor model-based algorithm design tools.

Computer vision and image understanding are being developed using knowledge-based software. Computer vision will be applied to autonomous smart weapons. A prototype image interpretation system is being developed for demonstration in the exploitation of imagery obtained from reconnaissance systems. Another program is developing model-based algorithms for the interpretation of synthetic aperture radar imagery. The algorithms are based on tactics, terrain, doctrine, and other battlefield limitations to deduce the existence of target arrays. In millimeter-wave sensor technology, algorithms are being developed using the data collected by a dedicated sensor designed to provide standard sensor data in several modes.

Other programs include automatic radar air-to-ground target acquisition (which will demonstrate a real-time implementation of model-based vision algorithm on a parallel processing computer using images derived from an airborne synthetic aperture radar), an ATR to counter camouflage, concealment, and deception (which will develop model-based vision algorithms to find camouflaged, concealed tactical targets among decoys and other enemy deception techniques using passive infrared and a carbon dioxide (CO^2) laser radar, and a strategic relocatable target (SRT)/automatic target cueing (ATC) capability, which is to demonstrate automatic cueing assistance to offensive weapon system officers looking for

Soviet relocatable missiles with an airborne synthetic aperture radar, as well as other candidate sensors, and combinations thereof.

DoD has a very aggressive technology base program in signal processing for phased arrays, particularly for acoustic arrays and conformal RF arrays (smart skins). DoD also is pursuing active and passive acoustic array technologies. Programs in acoustic arrays include high-gain conformal acoustic arrays, broadband arrays, ocean bottom sensors, and torpedo guidance and control. These programs are developing adaptive beam forming, matched filter processing, and target recognition.

RF conformal array (smart skin) sensors are also being actively developed for aircraft for multi-functional use (including radar, EW, and communication). Arrays of sensors will be dispersed or distributed over a large portion of the aircraft surface to provide very wide field of view sensing. Smart skins will provide greatly enhanced integration of avionics capabilities in conjunction with a superior ability to assess total situational awareness.

Total S&T funding[9] for this critical technology is given in the following table.

Funding--Signal Processing ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
580	130	130	140	140	140	150

3. Utilizing the Technology

DoD signal process research and development is focused on important generic application areas, such as

- Target, tracking, recognition, and identification
- Multi-sensor correlation/fusion
- Intelligence situation assessment
- Mapping and charting geodesy
- Speech recognition
- Text understanding;
- Indications and warning analysis
- Optical implementation of algorithms
- Adaptive antenna nulling/beamforming
- Smart skin technology

[9] Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

- Auditory localization
- Brain-actuated control
- Noise reduction
- Diagnostics (turbine engine reliability)
- Missile evasion
- Adaptive navigation.

Several strategic defense programs will have to address high-throughput signal processing in a hostile nuclear environment. The sensitivity of focal plane arrays (FPAs) to nuclear particle debris will require complex algorithms to compensate for excitations of detectors from this nuclear debris, which appear later in the processing flow as false targets. Because of the great number of detectors on the FPA, and the very high rate at which these detectors are sampled, enormous amounts of data must be processed to compensate for false targets from nuclear debris. Advanced monolithic wafer-scale integration technology promises the capability to efficiently combine high throughput and memory on a single wafer, allowing the implementation of the algorithms necessary for removing false targets induced by nuclear debris, while minimizing power consumption.

D. RELATED MANUFACTURING CAPABILITIES

DoD signal processing does not require special manufacturing so much as it does innovative applications of available processor power, logic, and algorithmic methods. Most of DoD's needs can be implemented using current microelectronics technology or through the evolution of photonics technology. Some special manufacturing requirements exist for the development of analog logic device and memory technology, which can be accomplished by modification of present digital electronics manufacturing techniques.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

In signal processing technology, the objectives of the DoD and other federal agencies are sometimes quite similar. There is interaction in the technology base with CIA, FBI, DEA, Coast Guard, and the Bureau of Alcohol, Tobacco and Firearms. However, signal processor system design, architecture, and algorithms are especially unique for weapon applications aimed at military-specific target classes.

To date, radar phased-array systems have been too expensive for use in air traffic control systems. The availability of lower cost, solid-state, active array modules, coupled with increasing requirements for higher traffic handling capability can be expected to make phased-array technology an area of greater interest for this application.

2. R&D in the Private Sector

Use of image processing and pattern analysis techniques is becoming widespread in the commercial sector. Medical imaging is one example that has important social implications.

University research has been a significant part of the emergence of many important facets of signal processing technology, such as neural networks, many of which are based on years of research at universities. Realizing the importance of the multi-disciplinary nature of neural networks research and the importance of bridging the gap between neurobiology and the engineering sciences, many universities have started a new curriculum on computational neuroscience. These basic science research efforts will undoubtedly lead to useful new neural network architectures and hardware implementations. Recently, university researchers have begun investigating the potential for wavelets in signal processing applications. DoD is sponsoring substantial university programs to take advantage of the potential multi-scale resolution capabilities of wavelets.

Acoustic-array and anti-submarine warfare (ASW) signal processing share a common technology base and were originally derived from marine seismic techniques. Research emerging in the area of geophysical processing may prove to be directly applicable to towed array systems.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Signal processing technology involves specialized sensors, processors, and algorithms for real-time acquisition, analysis, discrimination, and recognition of specific targets. Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Effective integration of improved sensor elements with intelligent signal processing functions
- Development of empirically validated algorithms
- Application of massively parallel processors and neural networks to signal processing.

The table on the following page provides a summary comparison of the US and other nations for these selected key aspects of this technology. The US enjoys a significant lead over other countries in the area of signal processing and in the development and use of the extensive data bases needed to support this effort. Effective application of the technology has the potential to reveal sensitive information regarding US threat intelligence and the inherent weaknesses of US systems.

While classification of sensitive information may preclude extensive cooperation on specific techniques and systems, much of the work ongoing in NATO, Sweden, and Israel could contribute to the advancement of signal processors and algorithms applicable to ATR.

Specifically in the area of high-speed data conversion (primarily analog-to-digital conversion), European efforts are proceeding in integrated bipolar and CMOS on a single chip (Bi-CMOS) under the ESPRIT program. Bi-CMOS is also the subject of independent efforts in the UK and the Netherlands.

In the area of processing algorithms and techniques, there is widespread activity. Both the FRG and the Netherlands are working on techniques for three-dimensional image processing and filtering for estimation.

Summary Comparison--Signal Processing

Selected Examples	USSR	NATO Allies	Japan	Others
Effective integration of improved sensor elements with intelligent signal processing functions	▨	□□	□□	□□ Sweden, Israel
Development of empirically validated algorithms	▨▨▨	□□	□	
Application of massively parallel processors and neural networks to signal processing	▨	□□	□□□	
Overall [d]	▨▨	□□ [a]	□□ [b]	□□ [c] Sweden, Israel

[a] While not predominant in any key aspect of this technology, the UK and France have specific capabilities of interest.

[b] In comparison to the United States, Japan has limited experience in fielding operational phased-array radars. Their experience in photonics and high-speed digital processing cam make a significant contribution to the US development of advanced signal processing.

[c] The sensitive nature of a signal processing technology may limit cooperative opportunities; however, technologies could contribute to critical component developments.

[d] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

Ongoing work at the Royal Signals and Radar Establishment, in conjunction with INMOS Ltd; and Oxford University is of interest for the development of massively parallel signal processors for sonar and radar applications. The FRG has developed a prototype phased array for air defense applications, and Thompson-CSF is reported to have a significant capability in phased-array design.

Interest in neural networks for signal processing has not been limited to the United States; both Japan and the European nations have made commitments to neural network research. Japan has initiated a government-sponsored program to look at the biological origins of neural networks, and firms such as Fujitsu have begun developing "thinking computers" especially for robotic applications. The Europeans, meanwhile, have begun a neural network-oriented program called ESPRIT II. The Netherlands and the FRG are exploring neural networks in two- and three-dimensional imaging. The UK has expressed an interest in radar processing applications. The Alvey program has a major effort in adaptive user interfaces that may provide benefit to future neural net applications. Finland and Sweden have research efforts in the use of neurocomputing to pattern recognition. Moreover, the International Neural Network Society was formed in the spring of 1987 and has grown immensely.

Although the Soviets appear to be aware of neural network technology, their efforts are still in the early stages, focused on developing computational models of neurons and the brain. In terms of hardware and VLSI technology, there is no evidence that they are trying to implement these neural network architectures.

2. Exchange Agreements

The high level of exchange activity in radar and in passive sensors is reflected in and supported by a high level of exchange in signal processing. The NATO Defense Research Groups (DRG) for Long-Term Scientific Studies and Long-Range Research Related to Air Defense, Optics and Infrared Technologies, and Electronic Warfare Concepts and Technology all will provide a mechanism for some level of exchange of fundamental requirements and scientific information in signal processing. The DRG on Identification of Submarines is directly applicable to passive ASW towed array signal processing.

The Technology Cooperation Program (TTCP) also provides mechanisms for a range of applicable exchange activities. Specific topics under TTCP support information exchange in signal and image processing for IR and electro-optical sensors, undersea acoustic signal processing for ASW, EW signal processing, and radar signal processing.

Each of the Services also has a significant number of exchanges with NATO and other friendly nations in all of the TTCP topics, and additional topics such as passive acoustic and seismic detection for ground systems and counter-intrusion detection. The Service programs also include exchanges in specific application of signal processing technology, such as space-based IR surveillance and airborne ASW acoustics.

10. SIGNATURE CONTROL

A. DESCRIPTION OF TECHNOLOGY

This critical technology enables the modification of signatures emanating from weapon systems, those characteristics by which systems may be detected, recognized, and engaged. Such signatures include radar and infrared signatures of aerospace vehicles, acoustic signatures of naval ships and submarines, and the visual profile of tanks. Some signatures result from emissions (radio, thermal, acoustic, or other) from the vehicle, and other signatures arise from natural or manmade energy as reflected by the vehicle, so that the vehicle contrasts sharply with its background. The reduction or other control of vehicle radar, infrared, and acoustic signatures greatly improves their survivability, resulting in improved weapons effectiveness.

The reduction of radar signature is accomplished by vehicle shaping, the use of radar absorbing materials to reduce radar echoes (mostly at microwave frequencies), and passive or active cancellation techniques. For example, the reduction of infrared signature is accomplished by cooling and by applying special materials for background matching (to reduce detection by passive systems). The visual outline of a tank might be modified with a camouflage net. The target strength of ships and submarines can be reduced by structural shaping and application of anechoic coatings. Radiated noise from hull and machinery is controlled by structural acoustics and fluid dynamic design. Clearly, the materials and concepts for reducing both radar and infrared signatures are critical to developing weapons systems with low signatures. The technology (materials, structural acoustics, and fluid dynamics) to reduce hull, machinery and weapon system noise is essential to maintaining US undersea warfare superiority. Recent and continuing Soviet advances in submarine and ship quieting are making anti-submarine warfare (ASW) more difficult and more expensive. As a critical adjunct to platform signature reduction, the signatures possessed by specific weapons and by installed systems must also be reduced. Rocket plume reduction is an important part of weapon signature reduction efforts.

In some scenarios, the objective is not signature reduction but rather signature control, typically for deception. Decoy vehicles should mimic the signature characteristics of the actual weapon systems, including not only the absolute levels but also the signature fluctuation or scintillation rates. As threat sensor capabilities improve there will be a requirement to mimic even the signature information that can be extracted via signal processing techniques, such as images. In some cases, the decoy signatures must be increased rather than reduced, for example, to increase the radar cross section of a small decoy until it looks like a ship on a radar screen.

Critical Technology Challenges for Signature Control

- Design (shaping) for low observability
- Radar absorbing materials
- Infrared signature reduction
- Acoustic quieting
- Visual and ultraviolet signature reduction
- Low probability of intercept radars and communications
- Deceptive emissions and decoys

B. PAYOFF

1. Impact on Future Weapon Systems

Reduction of the signatures of weapon systems significantly affects their design, support, and effectiveness. The utilization of signature reduction techniques can improve the penetration capability of strategic systems and the survivability and effectiveness of tactical systems. The use of signature reduction technology for strategic systems can render the Soviet Union early warning radar network less effective, thus allowing greater penetration with reduced weapon systems losses and flight plans at higher altitudes, thereby improving the capability to find and destroy targets. The reduction of the signature of tactical systems (such as air-to-air interceptors and air-to-ground attack aircraft) allows those aircraft to achieve higher exchange ratios and improved survivability. The reduction of both radar and infrared signature diminishes the threat of surface-to-air missiles, thus allowing the destruction of highly protected targets without serious loss of aircraft. Similarly, the reduction of both radar and infrared signature diminishes the threat of air strike munitions to ground vehicles and naval vessels. The deployment of decoys with proper signature control can saturate the Soviet Union air defense network or air strike capability, thereby minimizing the loss of aircraft, ground vehicles, and naval vessels by forcing the wasteful expenditure of threat munitions.

As the stealthiness of missile airframes and platforms increases, the missile exhaust plume signature plays a greater role in early detection. Lower visibility plumes will minimize detection of both the launching platform and the attacking missile and thereby enhance battlefield survivability. If critical launch platforms (aircraft, ships, tanks, personnel) are to be protected, then the plumes from rocket motors must be made far less visible.

The application of signature control technology will affect the system's support function. The introduction of new materials in structures and coatings will require new system support procedures. The use of signature control will require special test and evaluation procedures to verify the continued performance of the signature reduction techniques and methods.

Technology for acoustic signature control also counters losses in US undersea warfare superiority and will widen the margin of superiority in the future. It will also enable submarines and ships to undertake new missions.

2. Potential Benefits to Industrial Base

Signature control is primarily a military need, and the industrial base is largely dependent on government funding. Few significant commercial applications exist. One example is the covering of structures in crowded urban environments with TV-absorbing materials to reduce TV echoes. This application has been used in Japan but not in the United States. At least one US firm markets a radar absorbing cover for automobile front ends, and also radar absorbing materials are used in the construction of commercial radars.

C. S&T PROGRAMS

By the year 2000, advancements in radar signature control technology will allow the application of passive techniques to reduce the low-frequency radar signature of aerospace vehicles. Techniques and materials to reduce radar signature at very high frequency (VHF), and generally at frequencies well below the microwave region, will reduce the effectiveness of today's Soviet early warning network.

Also by this time, progress in the reduction of infrared signature in both the short-wavelength IR (SWIR) and long-wavelength IR (LWIR), along with radar signature reduction technology will render current Soviet Union surface-to-air and air-to-air missiles effective only at very close range.

Acoustic signature reduction is a Navy-unique critical technology being addressed by Navy programs in exploratory and advanced development. The technology is currently aimed at the next-generation attack submarine. Some technology base program products will be retrofitted to existing ships, submarines, and weapons before the year 2000 (e.g., quiet propulsors and acoustic materials).

Funding and milestone information for this critical technology comes mostly from classified sources and is not included in this report.

D. RELATED MANUFACTURING CAPABILITIES

Industrial process technologies critical to advanced signature control concepts for ships and submarines include computer-aided design and computer-aided manufacturing (CAD/CAM), computer-numerical control (CNC) machine tools, laser and optical hardware, and robotics. These technologies are important to propulsor and machine quieting. Important applications to aviation are engine manufacturers, structural component manufacturers, and specialty materials and coatings producers.

1. Current Manufacturing Capabilities

Existing domestic manufacturing capabilities that support machinery silencing are primarily in the areas of machining, casting, and molding. Other industrial concerns provide for manufacture of noise attenuation components and treatments. This domestic industrial base, in addition to the shipyards and Navy laboratories, provides the quiet components and materials for machinery silencing.

The control of the acoustic signature associated with the propulsor of a marine vehicle requires CNC machines to provide a more repeatable surface contour. Domestic centers that have a capability to manufacture large-scale submarine and surface ship propulsors are starting to employ CNC machines. Trade-offs are being made between the costs of machines, hand-finishing, programming, and the degree of signature control. Welding of a propulsor will usually lead to significant variations from the specified contour because of the excessive heat that must be applied.

Manufacturing capabilities exist within DoD weapon systems contractors and selected specialty materials manufacturers to support application of current technology to aviation systems.

The industries for gas turbine power plants, heat exchangers, and gas scrubbing support the reduction of signatures from exhaust gases.

2. Projected Manufacturing Capabilities

New and improved manufacturing capabilities will be required to transfer new signature technology materials to system applications that emphasize producibility, cost, and performance. Additional effort will be required to achieve close tolerance manufacturing and to develop adequate capability to remanufacture or repair DoD systems in the inventory.

For silencing ship machinery, expanded, cost-effective capability in precision three-dimensional machining is required. Increased capability in fabricating components from advanced materials, such as titanium, is required.

Silencing of ship propulsors requires that distortion, due to welding, and surface contour variations, due to hand finishing, be eliminated. This will be accomplished by incorporation of laser welding; its rapid moving, localized heat source minimizes heat-induced stresses. Multiple-axis CNC machines with computer processing will also be used to permit a complete machined definition of the blade surfaces. This will be accomplished with improved surface definition software and the integration of this software into a standard CAD system. Precision measurements of the blade surfaces and their position will be accomplished using a laser/robotics inspection system. The combination of these three advanced capabilities will provide a complete manufacturing work cell.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

This is a DoD-unique technology which is not of interest to other government agencies.

2. R&D in the Private Sector

DoD-sponsored university research efforts involving signature control technology include work in multi-functional polymers (with superior mechanical integrity in severe environments), ultra-structured ceramics materials design (with tailored IR signature absorption), and synthesis of macromolecular ceramic materials (for ultraviolet and visible-wavelength sensor protection).

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

While the United States is the recognized leader in developing signature-related expertise, the interest and technology available from other countries, most notably NATO allies, is expanding.

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Improved modeling and measurement of broadband scattering characteristics of complex shapes
- Structural radar-absorbing material (RAM) components and ferrites/polymer composites
- IR signature reduction (including propellants and plume)
- Acoustic signature reduction in marine platforms and techniques for dynamic balancing of complex rotating machinery
- Helicopter acoustic signature reduction.

The table on the following page provides a summary overview of foreign capability in these aspects of the technology.

The United States is the leader in developing low-signature propellants and has international formal data exchange agreements. The Services are attempting to reduce the visible, infrared, ultraviolet, and radar signatures of tactical missile motors. A four-powers agreement exists between the United States, the UK, the FRG, and France to develop high-energy, low-sensitivity, low-signature propellant technology.

The United States relies upon several countries for certain rocket propellant ingredients and other propellant development activities. However, the United States does not rely substantially upon others for research, manpower, or manufacturing processes related to low observability. While cooperative arrangements exist externally, the United States retains the capabilities to move ahead in this area.

Classification restricts access by any foreign country to information related to signature control. Generic RAM, however, is available to foreign enterprises. In fact, one of the largest RAM manufacturers in this country is foreign owned.

A promising area for cooperative research is the tailoring of composite materials to attain specific radio frequency characteristics, such as Japan's technology in conventional carbon fiber reinforced and advanced ceramics and promising research in Israel on techniques using carbon fiber. Precise control of fiber conductivity is one of the key elements in tailoring or reducing radar reflectivity.

Summary Comparison--Signature Control

Selected Examples	USSR	NATO Allies	Japan	Others
Improved modeling and measurement of broadband scattering characteristcs of complex shapes	▨	□□	□□	
Structural RAM components and ferrites/ polymer composites	▨	□□	□□□	□□ Israel
IR signature reduction, (propellants and plume)	▨	□□	□□	
Acoustic signature reduction in marine platforms plus, techniques for dynamic balancing of complex rotating machinery	▨▨	□□	□	□ Israel
Helicopter acoustic signature reduction	▨▨▨	□□□	□	
Overall [a]	▨	□□	□□	

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

2. Exchange Agreements

Because of the high level of classification, few specific agreements could be identified for this area.

11. WEAPON SYSTEM ENVIRONMENT

A. DESCRIPTION OF TECHNOLOGY

Due to the increasing sensitivity of each generation of weapon system sensors, DoD systems and tactical operations are increasingly influenced by the natural environmental conditions (e.g., weather, seasons, terrain). The limitations and potential leverage of environmental factors must be clearly understood to increase existing system capabilities and performance or to optimize the design of new systems. Specific technological elements include wide area and high-resolution remote sensors, data acquisition systems, analysis and predictive numerical codes, tactical environmental data processing, and decision aids developed from environment-system effects analyses.

Weapon system environment technology differs from other critical technologies in that it does not develop specific hardware. It is included because it is critical in the selection, development, and operation of superior weapon systems, for such missions as anti-submarine warfare (ASW), battlefield surveillance, and communications.

Critical Technology Challenges in Weapon System Environment

- Underwater acoustic propagation
- High-resolution environmental remote sensing
- High accuracy environmental prediction
- Scene models for system design and evaluation

B. PAYOFF

1. Impact on Future Weapon Systems

The weapon system environment will become more crucial due to three factors:

- The next conflict may not be one of attrition; success of the first engagement may be critical to the outcome.
- Countering quiet submarines and low-signature aircraft and missiles demands fine-grained environmental data.
- Low-intensity conflicts increase the need for real-time environmental data.

Simulations have indicated that by using proper environmental data, the theoretical probability of acoustic detection of submarines can be increased by 30 to 40 percent, the range of the first detection extended by 20 to 80 percent, and the duration for which a contact is held lengthened by 20 to 40 percent. Improvements of this magnitude are crucial to counter adversary submarine quieting and regain the ASW advantage once enjoyed by US forces.

Current smart weapons (SW) systems have high false alarm rates when tested in a variety of environmental conditions. Integration of comprehensive environmental knowledge into the logic modules, design, and testing and evaluation of these systems will dramatically reduce false alarms and increase their effectiveness.

Electro-magnetic fluctuations in the ionosphere degrade over-the-horizon (OTH) radar range and azimuth performance, and especially degrade the capability to detect low-observable targets at night. Ionospheric modification to create regions of enhanced ionization may enhance overall radar performance, day and night; permit surveillance and target acquisition at closer, possibly tactical, ranges; and enable high-resolution detection and tracking of very small radar cross-section targets. Magnetic ASW and minehunting sensors, spaceborne systems, and communications performance are also adversely affected by ionospheric disturbances. The development of predictive ionospheric models will enhance OTH frequency management for maximum effectiveness, help protect spaceborne systems, and permit maximum effectiveness of magnetic sensor systems.

Targeting and mission planning, including the choice of weapons and tactics, depend largely on the tactical environment in which they will be used. High-resolution weather prediction techniques and algorithms known as electro-optical tactical decision aids (EOTDAs) are being developed to assess probable target signatures, background signatures, and atmospheric effects. The products available to the tactical commander will permit proper selection of weapons and tactics for the given target and the expected environmental conditions.

Testing has shown that current imaging and detection systems are not optimized for atmospheric conditions. Using knowledge of environmental effects, researchers have, through selective filtering, optimized the performance of infrared (IR) sensors to provide an order of magnitude increase in the signal-to-noise ratio of currently fielded IR systems. In addition, understanding the effects of atmospheric conditions on terrain propagation of seismo-acoustic signals will enhance the performance of ground-based seismo-acoustic sensors for weapons targeting and passive battlefield surveillance.

2. Potential Benefits to the Industrial Base

The industrial base of the United States will enjoy a variety of benefits from research in this area. Examples include marine and atmospheric weather prediction for disaster warning, optimal aircraft and ship routing, and the utilization of knowledge of the sea for predicting optimal fishing locations. Remote sensing of the environment will provide insights into crop optimization; improved remote detection and weather prediction capabilities will provide advanced warning of danger over land areas and at sea. Improved coastal oceanographic and meteorological knowledge will directly affect coastal and harbor construction designs. The accurate prediction of coastal phenomena will benefit the coastal construction and recreation industries.

Goals and Payoffs--Weapon System Environment

Application	Goal	Payoff
Oceanography	• Predict global and mesoscale ocean circulation • Predict marginal ice zone movement, behavior, and boundaries • Understand dependence of small-scale oceanography on larger-scale properties	• Tactical support of employment of surveillance assets and weapons • Improved support to search, rescue, and salvage operations • Improve localization for weapon systems
Underwater acoustics	• Describe and predict acoustic propagation in shallow and deep water environments • Improve performance prediction of bottom-mounted sensors • Model under-ice acoustic interaction	• Passive range and depth localization combined with detection • Broadband acoustics signal processing to offset narrowband quieting • Improved localization of under-ice targets • Reduced false targets
Meteorology	• Accurately forecast global, regional, and local weather (7 to 10 days, 3 to 5 days, and 24 hours, respectively) • Describe and predict atmospheric boundary layer (surface to 1,000 m) phenomena • Improve tropical cyclone forecasting • Understand environmental effects on weapons systems	• Improved performance of surveillance and C3 systems (electro-magnetic and electro-optical) • Incorporation of real-time environmental effects into battle management and system operation • Tactical ship and aircraft routings, reduced damage to ships and cargo, fuel savings, covert movement of forces • More effective weapons systems development, deployment, and decision aids for the operational commander
Remote sensing	• Provide real-time quantitative data worldwide • Supplement observing networks in data sparse and data denied areas • Provide boundary data on marginal ice zone • Locate and identify major ocean features and weather systems • Develop sensing techniques extending environmental parameter coverage	• Rapid mapping of regions of interest • Improved initialization of prediction models for forecasting • Sensing capability over remote areas • Tactical support to battle management and weapons employment • Enhancement of weapon system design and testing
Ionosphere	• Describe and predict ionospheric disturbances and hazards • Develop modification techniques	• Protection of space assets • Enhance perfomance of over-the-horizon radar

C. S&T PROGRAMS

1. Milestones

Milestones--Weapon System Environment

Application	By 1995	By 2000	By 2005
Oceanography	• Global predictions of ocean circulation • Regional predictions of mixed layer	• Eddy-resolving global circulation prediction • Basin scale nowcast forecast system • Shipboard tactical "nowcast" forecast models	• Global eddy resolving "nowcast" forecast system • Shallow water high resolution (less than 5 km) prediction models • Operational detection methods • In situ measurement link by satellite
Underwater acoustics	• Range dependent 3-D acoustic models with emphasis on broadband low-frequency propagation	• Broadband acoustic signal processing capability • Multi-static active acoustic model	• Passive range and depth localization combined with detection • Acoustic warfare model
Meteorology	• Environmental model of arctic regions atmosphere/ice/ ocean • Quantification of major non-linear scale interactions from field experiments	• Signal propagation/air-sea interface model • Incorporate EO tactical decision aids into battle management systems • Regional prediction of high-resolution atmospheric boundary layer evolution	• Fully coupled model of atmosphere/ocean/weapon system • An effective high-resolution/ forecast capability for adverse weather and terrain
Remote sensing	• Field experiment of integrated remote sensing systems for environmental measurements • Quantification of environmental background effects	• Proof of concept of synergistic systems for environmental measurements • Target acquisition and recognition prediction capability	• Integrated synergistic expert systems for environmental assessments
Ionosphere	• Small-scale modification experiment	• Proof-of-concept demonstration of modification technique for OTH radar surveillance	• Coupled ionosphere predictive models and modification techniques for OTH operations support

2. Developing the Technology

a. Atmospheric Prediction

The physical processes governing mesoscale atmospheric (500 to 800 km) dynamics are, in general, known well enough for the serious pursuit of predictive systems to support tactical decisions regarding weapons system employment. Recent modeling of atmospheric processes at battlefield scales is demonstrating that the computational power is nearly available, that numerical techniques are improving rapidly, and that the data requirements for the predictive models may be achievable. High-resolution tactical atmospheric models will be developed to integrate locally acquired battlefield data with regional or global data to support the tactical commander with definitive 3- to 48-hour forecasts for weather conditions in the tactical area of interest. High-resolution predictions for rainfall and electro-optical/infrared (EO/IR) propagation, for instance, will be coupled directly with terrain models to generate mobility predictions for tactical planning and EO/IR target signature and background predictions for weapons selection.

b. Ocean Modeling and Underwater Acoustics

Similar to atmospheric modeling, ocean circulation and structure models are progressing rapidly but are heavily dependent on sparse surface and undersea data sources. High horizontal resolution, eddy-resolving ocean circulation models are being coupled to ocean basin and high-resolution, mixed-layer models to resolve the ocean with sufficient detail for improved performance prediction of acoustic ASW systems. Future improvements include the coupling of the atmosphere of the ocean mixed layer through the addition of a marine boundary layer model, which will include two-way feedback between the ocean and the atmosphere. Acoustic tomography and other advanced in situ oceanographic measurements will help provide real-time input for the predictive models and for developing a tactical oceanographic data base. New techniques in data acquisition from various sources and for data assimilation into the numerical models are required if the predictive systems are to perform acceptably.

Underwater acoustics drives much of the ocean modeling effort with the objective of supporting the successful development and use of ASW surveillance systems, ASW weapons systems, and ASW countermeasures. Technology goals are directed to more effectively detect, localize, and track high-performance threat submarines; the thrust areas include active sensor systems, arctic systems, and seismic sensors. Bottom-scattering and reverberation models are the primary acoustic propagation elements of the active system, supporting both the battle group multi-static sonar system and the low-frequency active acoustic system. Determination of high-resolution directional ocean noise properties is essential to the performance of planned high-resolution active and passive sonar systems. New spatial and temporal statistical measures support the new acoustic system development efforts as well as operations strategy.

c. Scene Dynamics

Measurement and modeling of the dynamic electro-magnetic (EM) and seismic/acoustic character of terrain and the atmospheric boundary layer is leading to the realistic simulation of scenes for evaluation of conceptual and prototype smart weapon/automatic target recognition (SW/ATR) systems. Simulation allows early consideration of a variety of operational conditions in weapon design as well as optimization of test and evaluation efforts and the translation of sparse test data to a variety of other conditions and scenarios. The Balanced Technology Initiative (BTI) program on smart weapons operability enhancement is the integrating force for DoD technology base efforts to consider systematic incorporation of environment into the research, development, test, and evaluation process for SW/ATR devices.

d. Remote Sensing

Current remote sensing efforts are focused on understanding the variation of individual environmental parameters, such as winds, temperature and moisture, using active sensors, such as lidar and radar, and passive sensors such as infrared. Future efforts will focus on developing the concept of integrated, synergistic expert systems for environmental measurements with global coverage from both surface (including ocean interior) and space-based platforms.

Underwater, non-imaging sensors offer alternative and supplemental information needed to develop and support future weapons systems. However, before acoustic technology can be exploited to advantage, environmental effects on propagation and signal-to-noise must be understood. The use of multiple sensors in weapons systems requires quantifiable knowledge of the limitations imposed by environmental effects.

Total S&T funding[10] for this critical technology is given in the table below.

Funding--Weapon Systems Environment ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
620	180	210	220	210	200	200

3. Utilizing the Technology

This critical technology relates to virtually all aspects of the DoD investment strategy in that all weapon systems and military operations depend on the environment in which they operate. This fact has been demonstrated repeatedly in systems development and in the adverse effects suffered by fielded systems inadequately designed for the tactical environment.

Major programs utilizing oceanographic data include

- The ASW environmental acoustic support program to provide improved operational and design data for long- and short-range acoustic surveillance systems.

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10 Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

- The acoustic performance prediction program that is utilizing ocean forecast models to improve ASW acoustic prediction capabilities.
- The air-ocean prediction program to provide improved data for weather forecasting at sea by incorporating air-sea interactions.
- The fleet air-ocean equipment program that is directed toward improved data collection and dissemination equipment.
- The tactical environmental support system program to upgrade single-station forecast capabilities by improved fusion of local data with forecast model inputs from central facilities.

Major Navy systems under development that are being supported by these efforts include the high-gain sonar array program and the low-frequency active sonar program in ASW.

Major programs utilizing atmospheric, space, and terrain data include the suite of SW/ATR devices being developed in the Army and Air Force (with a nearly $100 million near-term investment) and the Strategic Defense Initiative Office (SDIO) Phase I systems. Devices such as the search and destroy armor (SADARM) munition, wide-area mines (WAM), and sensor-fuzed weapons (SFW) demand critical knowledge of the environment to be used and operate effectively, as has been demonstrated in recent tests. Consideration of the environment early in the design stages and the ability to optimize and translate test results are critical to successful and affordable realization of multi-sensor fusion and autonomous decision-making capabilities.

The tactical employment of JOINT STARS will be directly affected by environmental events. JOINT STARS will require theater-scale forecasts of precipitation intensity and duration in target areas and forecasts of atmospheric refraction for anomalous propagation. Tactical battlefield forecasts for JOINT STARS are critical for successful management of offensive and defensive forces. Precipitation can reduce signal-to-noise ratios below acceptable limits and interrupt satellite communications links. High-resolution forecasts of precipitation events will permit real-time management of system resources and capabilities to minimize the effects of weather.

The Army is developing tactical weather system concepts to support the local commander with special forecasts and decision aids for tactical planning operations and weapons selection. When available, battlefield-scale forecast models for the 3- to 48-hour forecast will be integrated to provide the accuracy necessary for detailed next-day planning. The system will be located at different echelons of command and operated by the Air Force weather officers and teams.

D. RELATED MANUFACTURING CAPABILITIES

Definition and prediction of weapon systems environments has no manufacturing or industrial base component in the conventional sense. This technology is critical to the design and employment of systems.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

The National Oceanic and Atmospheric Administration has the primary responsibility for observation and dissemination of weather data and forecasts in the United States. This agency also sponsors a prototype regional observing and forecasting system (PROFS), which is attempting to address processes on battlefield scales. Research into atmospheric and oceanographic processes is also conducted under sponsorship of NASA, the Department of Energy, the Environmental Protection Agency, the National Science Foundation (NSF), and the Department of Agriculture (Forest Service). These agencies use in-house and contracted capabilities to achieve their research objectives. NASA and NSF sponsor limited research in oceanography with NASA remote sensing efforts followed closely by DoD.

2. R&D in the Private Sector

Industry R&D is very limited and primarily related to construction practices and pollution control. It is particularly noteworthy that the ocean and atmospheric technology base in the United States is crucially dependent on federal investment; for example, available data indicate that the IR&D investment in geophysics is less than 5 percent of the Air Force investment, while the IR&D investment in electronics is 500 percent of the Air Force's. The limited industrial R&D is a primary reason that environmental R&D is a critical technology for the DoD.

The Services have pursued this technology under the University Research Initiative and Small Business Innovative Research (SBIR) programs and will continue to do so. The military environment has not been the subject of major IR&D investment because it is not a capability commonly found in US industrial firms.

Universities also contribute indirectly to this technology area through efforts in studying weather forecasting, climatology, ionospheric physics, meteorology, and other atmospheric, oceanographic, space, and geological research.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Because of international cooperation in oceanography and meteorology, there is a high level of international activity and capability directly relating to important military applications. These efforts all contribute to our understanding of and ability to model complex tactical conditions and scene dynamics.

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Undersea acoustic research, especially that correlated with bathymetry data
- Accurate predictions of localized weather conditions

- Effective integration of remote sensing data
- Improved modeling and simulation of scene dynamics.

The table below provides a summary comparison of the United States and other nations in the key areas of this technology.

Summary Comparison--Weapon System Environment

Selected Examples	USSR	NATO Allies	Japan	Others
Undersea acoustic research, especially that correlated with bathymetry data				
Accurate predictions of localized weather conditions				
Effective integration of remote sensing data				Various nations
Improved modeling and simulation of scene dynamics				
Overall [a]				Various nations

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States

- significant leads in some niches of technology
- generally on a par with the United States
- generally lagging except in some areas
- lagging in all important aspects

Capability of others to contribute to the technology

- significantly ahead in some niches of technology
- capable of making major contributions
- capable of making some contributions
- unlikely to have any immediate contribution

The Soviet Union is most capable in some areas of the weapon-target environment, as in the theoretical and mathematical aspects of underwater acoustics. The United States and its NATO partners lead in the tactical employment of environmental products due to a technological lead in high-technology computers and related software and hardware.

DoD capabilities in weather forecasting exceed those of the Soviet Union for most of the globe. For example, US tropical cyclone forecasting capabilities far exceed those of the Soviet Union. However, in the Arctic, a more significant region tactically, Soviet knowledge of weather exceeds that of the United States because of greater experience, better facilities (such as ice-breaking research ships), and a broader research base.

It is generally accepted that the European Center for Medium-Range Weather Forecasting is the finest facility in the world for producing highly reliable and accurate 3- to 5-day weather forecasts. However, sub-grid scale phenomena and subtle changes in atmospheric fields critical to 3- to 48-hour forecasting, especially over the oceans where data is scarce, continue to prove troublesome even for this facility.

Agreements with NATO and other Western nations are common in environmental research. The global nature of the atmosphere and the oceans makes such cooperation comfortable and obvious. An example of an existing agreement involves work with the West Germans on the interpretation of synthetic aperture radar signals from the sea surface. NATO supports a major laboratory at LaSpezia, Italy, which is directed toward understanding ocean sciences and its effect on ASW. Recent studies have stressed shallow water ASW--a high priority for our NATO allies. The Army has a data exchange agreement with Canada on atmospheric effects, and is participating with other NATO countries in a major field evaluation of EO/IR sensors under a variety of atmospheric conditions.

With increasing reliance on satellite-based remote sensing, technologies for improved collection and integration will advance and proliferate. India, China, Brazil, and other countries are actively pursuing technologies for this purpose at varying levels.

2. Exchange Agreements

There is a moderate level of exchange activity in the area of oceanography, weather, and atmospherics. Several NATO Research Study Groups (RSG) of the Defence Research Group (DRG) (especially the RSG on Optics and Infrared Technologies) provide a potential mechanism for exchanges of fundamental scientific information in underlying phenomenologies of interest.

The Technology Cooperation Program (TTCP) provides a vehicle for a range of applicable exchange relating to both undersea systems and atmospheric propagation.

The Services have a number of exchanges, primarily in NATO but also with a few other friendly nations, in areas of specific interest. Predominant among the areas represented by these exchanges are oceanography, undersea acoustics, and atmospheric effects on IR sensors and propagation. Programs with France and the UK are focusing on the effects of atmospheric electricity and electro-magnetic affects on aircraft.

The exchanges in characterization of the atmosphere in the infrared region of the spectrum support key tactical weapons, strategic defense, and wide-area surveillance and intelligence. Different aspects of basic atmospheric physics and sensor performance are covered under Air Force, TTCP, and NATO DRG exchanges.

A number of agreements in the area of applied oceanographic and undersea acoustic research exist; however, because of the relationship to ASW, these tend to be classified programs and restricted to NATO allies except in cases where there is a clear quid pro quo.

12. DATA FUSION

A. DESCRIPTION OF TECHNOLOGY

Dramatic advances in data processing technology have enabled significant advances in command, control, communications, and intelligence (C^3I) and battle management during the past 20 years. Data processing technology has advanced to the point where many functions previously performed by military operators and intelligence analysts can be performed effectively by data processing systems. The increasing complexity and speed of warfare, when combined with rapid advances in computer and communications technologies, are driving the more effective integration of multiple sensors and diverse sources of information. Data fusion is the process by which multi-source and multi-modal data are combined to produce useful and readily interpretable information products through data reduction, synthesis of new information constructs, and man-machine interaction. Underlying technology development areas include collection and modeling of target signatures, algorithms, sensors combined with processors, testing and verification, and heterogeneous systems integration.

Critical Technology Challenges for Data Fusion

- Man-machine interface
- Distributed real-time systems
- Multi-level security
- Algorithm development
- Expert system development

Data fusion technology includes data processing techniques for a wide range of military applications from battle management to cockpit display integration. It involves the acquisition, integration, filtering, correlation, and synthesis of useful data from diverse sources for the purposes of situation/environment assessment, planning, detecting, verifying, diagnosing problems, aiding tactical and strategic decisions, and improving system performance and utility. In addition to military applications, high-speed, low-cost, reliable techniques for data fusion are of growing importance to automated manufacturing. Also, developments in improved testing and verification methods and heterogeneous systems integration are expected to find important commercial applications.

Data fusion is deceptively simple in concept but enormously complex in implementation. The essence of data fusion is the automated correlation of different signals and the resolution of ambiguities that are inevitable in an electronically dense battle zone. Data fusion provides

- *C^3 systems improvements:* Data fusion requires assured connectivity between sources and fusion center, timely communications service, distributed and redundant data bases, and extensive interoperability in the form of data item definitions, dialogue protocols, and explicit procedural standards to ensure quality of the input and output.

- *Expert system development*: Traditional expert systems attempt to capture and replicate human reasoning in a specific area. Data fusion goes beyond this level of complexity by addressing the next level in the hierarchy, the integration of different areas of expertise to form a more comprehensive awareness. The process must attempt to reason under uncertainty and must withstand ambiguity. Data fusion systems will have to resolve conflicts in sensor reports and must deliver products that gain user confidence.
- *Multi-level security*: To realize operational potential, a data fusion system requires access to highly classified intelligence that must be protected by reliable processes. The use of sensitive information in an automated system raises immediate issues of quality, reliability, assured access, assured exclusion, and protection of sources.
- *System integration and product utilization*: Estimating sensor outputs, communications network capacity, transit times, user query traffic, and the effects of the system's products on its own operation implies strong design and management authority over both services and functional communities. This degree of control has yet to be achieved in complex technology development programs. The operational user's access to data fusion products will present alternatives that could significantly affect the performance of the data fusion system itself. Various members of the recipient community may wish to ignore, exploit, deceive, jam, or destroy enemy systems that the data fusion system is using as critical inputs. A mechanism for adjudicating conflicts in use of data fusion products will be required before the system enters operational status.

B. PAYOFF

1. Impact on Future Weapon Systems

Data fusion technology offers significant opportunities for advanced battle management and C^3I systems. Operations in the future will develop faster and have much greater destructive capacity than in the past. Commanders will have considerably less time to make decisions and much more data to base decisions on. The decisions they make will have more significant and far-reaching consequences than in the past. Without some form of automated data fusion, military personnel may be overwhelmed by data that could contribute to errors in judgment or delay of decisions and lead to catastrophic results.

The demand for data fusion capabilities has reached a critical level because of a number of operational technological and threat-related developments. The evolution of US operational doctrine (which emphasizes deep attack and interdiction capabilities) created a concurrent demand for information describing the location, movement, and intentions of targets beyond the performance of conventional sensors. Autonomous weapons, developed to execute deep-strike missions, currently require a priori assurance that they will encounter a target within their range of coverage. The coming generation of combat vehicles, vessels, and aircraft is being designed to exhibit very low signatures to radio frequency and infrared (IR) sensors. To preserve their low observability, they will rely on passive sensors and information received from remote sources. Fusion of these inputs is an essential step in the development of the situational awareness required for survival and effective operation.

Data fusion techniques are essential to counter adversary use of stealth technology (e.g., acoustic quieting, low radar cross sections, low IR signature) and to aid in wide-area target surveillance in hostile and cluttered environments. Data fusion is particularly important for global or large-area surveillance and targeting. It will assist theater and lower echelon commanders in wide-area surveillance from space as well as undersea, predicting environmental conditions, and managing distributed assets (such as in electronic warfare). Data fusion will also assist platform commanders such as Advanced Tactical Fighter/Advanced Tactical Aircraft (ATF/ATA) pilots in their future "super cockpit" or helicopter pilots with their nap-of-the-earth navigation.

2. Potential Benefits to Industrial Base

High-speed, low-cost, reliable techniques for data fusion are of growing importance to automated manufacturing, in the defense and non-defense sectors. Real-time process control, sensor-directed cells and workstations, and robot and effector manipulation are three examples of manufacturing initiatives aimed at making products faster and with higher quality, which will require advances in data fusion technology. Other areas that could prove to be of substantial benefit to the commercial sector include heterogeneous systems integration, which is aimed at the development of distributed operating systems to allow the interchange of processing between disparate processors, such as when equipment made by unrelated companies must interface. Another area that shows great commercial promise is development of an object-oriented data base management capability. This technology could eliminate the writing of new software code as data base requirements change.

The development of sophisticated distributed data base systems required by DoD data fusion applications will also find application in the civil sector in urban planning; resource management; pollution monitoring and analysis; and climate, crop, and geological analysis by supporting efficient information sharing among diverse agencies and organizations. The development of intelligent data base shells will simplify and reduce the development time of application software by supporting higher level interaction with the data base system.

C. S&T PROGRAMS

1. Milestones

Milestones--Data Fusion

Technical Area	By 1995	By 2000	By 2005
Model development		• More reliable fused prediction models for: UV, IR, laser radar, radar, ESM, RWR	• Addition of high countermeasures environment capability
Fusion algorithm demonstrations	• Combined track, file, ID, and fire control fusion in real time	• Two-dimensional radar and EO sensor data fusion using feature-based algorithm	• Complete and evaluate high-fidelity algorithm fusion suite for ID and fire control with UV, IR, laser radar, ESM, RWR
Data fusion applications	• SIGINT digital data fusion systems (non-real-time leading to real time)	• Improved pre-detection sensor integration with improved clutter suppression and low observable visibility • Real-time SIGINT processor tests	• Demonstration of integrated sensor/fusion processor with all signal processing done at central location for optimal suppression and low observable visibility • SIGINT expert analyst/interpreter
Secure distributed real-time operating system	• Mach fully operational and transferred to the industrial base	• Trusted Mach with real-time features ready to support classified operations	• Next-generation distributed services based on Mach with persistent object concepts
Distributed data base	• Distributed transaction systems available National-scale distributed file system operational	• Prototype replicated distributed data base with dynamic synthesization of data from nodes not on network	• Fully distributed data model with consistency management to enable operation through communication outage

2. Developing the Technology

The DoD program for the development of data fusion technology includes collection and modeling of targets and backgrounds, algorithm development, hardware development, and systems integration and testing. Although automated single-source fusion (such as target association and tracking based on statistical process models) is reasonably well developed, great benefits may be derived from techniques to utilize and automate the vast amounts of non-sensor derived domain knowledge typically used by human analysts. Additional basic research is required to ensure the proper development and selection of synergistic sensors and the development of architectures and algorithms that fully exploit the information derived from a great variety of sensors.

Advanced model-based vision techniques are being developed to enhance confidence in multi-sensor fusion used for target acquisition and identification. Initial efforts focus on intra-radar signature fusion in which an algorithm suite will exploit ultra-high resolution ranging radar. Expansions will include threat warning, IR, laser radar, and ESM sensor inputs under the multi-attribute ID analysis program. The result is a comprehensive algorithm suite for fusing multiple sensor inputs for air and ground targets at a feature level.

A significant DoD data fusion program involves distributed command control. This program is designed to provide an evolutionary method of making the transition from present standalone military systems to high levels of information exchange made possible by distributed computing technology. Another important effort is the inter-Service program on the Cronus distributed operating system. This operating system allows the interchange of processing between heterogeneous processors. A new distributed operating system is the DoD-sponsored Mach operating system technology. This technology is adaptable to UNIX machines only but has great potential. Complementary to the development of Mach is the development of a trusted Mach (which will provide security for distributed systems). Another DoD effort is the development of an object-oriented data base management system capability. This technology shows promise in eliminating the need for writing software code as data base requirements change.

The Mach operating system, initially a university effort, has become the foundation for the advance of the industrial base of operating system development. Mach has been run on numerous computer architectures (including all major microprocessors) as well as on large-scale multiprocessors. It has even become the operating system base for a 1.6 billion floating point operation per second supercomputer. On the immediate horizon are a number of advances to the Mach operating system such as real-time and multi-level security. During the next three years, real-time features will be added to Mach to allow services to be developed cost effectively without being tied to specific computer hardware. The Trusted Mach project, which will add National Computer Security Center B3 level of protection to Mach, will represent the first truly portable, multiprocessor, distributed secure operating system.

A pivotal hardware component under development is a rugged, high-resolution, flat-panel display that is viewable under all ambient light conditions and operational under tactical environments that cover extreme conditions of temperature, shock, vibration, moisture, and dust. A significant program is developing an electroluminescent (EL) flat-panel display for tactical military systems. A 3-by-5-inch EL flat-panel display (with a resolution of 190 x 320 lines) is incorporated into the Digital Message Device; and three EL displays, including a 5-by-6.5-inch display with a resolution of 512 x 640 lines, will be in the M1A2 tank. The DoD is also evaluating the effectiveness of liquid crystal flat-panel displays for tactical systems.

DoD is developing battlefield-scale meteorological models and using expert system techniques to gather and fuse (temporally and spatially) varying meteorological data from all sensors on the battlefield into a structured meteorological data file and array. Results of this fusion process will be used for tactical combat situations and for training exercises.

The battlefield of the future will move at a rapid pace. Sensors and weapons will identify targets on a real-time basis. Data processing techniques are needed to fuse, process, and analyze data from many sensors and present usable results almost instantaneously. DoD's Pilots' Associate program is an example of such an effort. This program fuses all sensor and C^3 inputs and provides needed information to the pilot. The Air Force's Super Cockpit program provides another example of data fusion on a vehicle platform. This program is developing ways to better present mission and aircraft status information to the pilot's eyes and ears in a three-dimensional format. It will include fusion of sensor and stored terrain information within aircraft avionics and will eventually incorporate artificial intelligence to reduce the pilot's workload. The development of the algorithms and associated software to make such systems useful is a significant part of this and related programs.

The Army's LHX program includes the development of both internal (system) and external (environmental) status. An effective display of the vehicle environment (including hazards and targets), provides the first step in a decision-making aid. With the addition of expert systems based on vehicle/armament performance knowledge, the vehicle commander can be provided with alternative options to cope with an array of tactical problems. Demonstrations of these capabilities for both Apache and LHX helicopters will be conducted in the mid-1990s, based on current technology base efforts.

Data fusion programs go beyond individual platforms to more complex decision-making aids--a battlefield management system. By being able to fuse huge amounts of information, this technology can provide much more efficient tools for battle management assessment, timely decision making, rapid replanning, and survivability through distribution of tasking, machines, and data repositories.

In undersea surveillance, the Navy has numerous signal processing technology programs aimed at fusion of signals detected by different acoustic arrays. Current systems are highly labor intensive. Proliferation of threats greatly increases the volume of data to be processed and automation of the target recognition process is needed.

Total S&T funding[11] for this critical technology is shown in the table below.

Funding--Data Fusion ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
210	50	50	50	50	50	50

3. Utilizing the Technology

A significant DoD program is the distributed integrated electronic warfare (IEW) fusion system that is designed to receive input data from an integrated sensor system (via multi-level security channels), perform adaptive intelligence fusion/analysis of data, and utilize self-learning capability to enhance system performance. This effort, which is intended to assist in planning, directing, and controlling battlefield operations, will be the

[11] Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

subject of various subsystem demonstrations during the 1991-96 timeframe. The Army has established a tactical intelligence data fusion testbed for the development and analysis of fusion software.

A first-generation demonstrator system has been upgraded to operational use in central Europe and several terminals are located in Allied facilities. US Army (all-source analysis system) and US Air Force (enemy situation and correlation element) developmental efforts are underway to produce a more powerful successor generation. Within NATO, the battlefield information collection and exploitation system project is developing an architecture and standards to allow interconnection of the collective national resources of the Alliance in a theater-wide network of sources and fusion centers.

The wide-area mine system has been augmented by acoustic and seismic sensors that can detect vehicles up to 300 meters, and distinguish between tracked and regular vehicles, heavy and light armed vehicles, and US and Soviet vehicles. After the target is distinguished, it is located and attacked by appropriate means. The mine is equipped with sufficient electronics to perform the data fusion without human assistance.

DoD is also developing an automated information retrieval system (consisting of hardware and software) that will provide explosive ordnance disposal teams with a man-portable system able to operate in a tactical environment. The system will replace a data base of more than 15,000 pages of paper and 1,600 sheets of microfiche. Flat-panel displays are key hardware components.

The inter-vehicular information system/radio interface unit segment of the M1A2 tank system provides real-time processing and distribution of combat information to enable the integration and synchronization of critical battlefield information at battalion level and below.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

Data fusion will require communication systems and networks (with high data throughput) that are survivable in the face of enemy jamming, interception, and spoofing. Multi-computer systems for distributed data processing and distributed data base systems are required as are the software and software engineering technology to run them. Graphics software, advanced displays, and visualization technology linked with man-machine interface and human factors engineering also will be needed. Of fundamental importance (from a manufacturing perspective) is the ability to fuze data across organizations. The development and manufacture of high-resolution, flat-panel displays is also important to data fusion.

The essence of this critical technology is that disparate sensor information is appropriately preprocessed, melded, and only pertinent information extracted and presented. The components of technology required to build systems of this type is thus contained elsewhere (see, for instance, semiconductor materials and microelectronics circuits, active and passive sensors, and parallel architectures). However, the fact that manufacturing processes can exploit subsets of this technology is of fundamental importance to the industrial base. Real-time process control, sensor-directed cells and workstations, and robot end effector manipulation are just some examples of manufacturing concerns requiring data fusion.

2. Projected Manufacturing Capabilities

Manufacturing advances will depend largely on developments in computer and communication technologies, automated decision making (well beyond current expert system technology), and other process-level activities. Artificial intelligence related efforts such as those directed at self-improving capability to enhance system performance and the extraction of understanding from multiple data sources are deemed particularly critical. Advances will come primarily from computer software and systems integration industries.

Other contemporary DoD manufacturing technology investments supporting and utilizing this critical technology include developing information engineering tools to support planning, analysis, and design of factory-wide information systems; participating in industry-wide, machine-to-machine interface and communications standards; and developing factory modeling and simulation techniques to assist in transferring products from design to production.

On a systems level, data fusion will be spurred by investments from Strategic Defense Initiative Office (SDIO) and DARPA initiatives, such as Pilots' Associate. However, none of these systems-level investments directly motivate manufacturing, nor will they demonstrate how data fusion can be used to make products faster and with higher quality.

E. RELATED R&D IN THE UNITED STATES

There are many similarities between the distributed processing technology efforts in US industry and DoD data fusion efforts. Consequently much beneficial interaction between DoD and industry is expected as applications proliferate. Most of the software and computer hardware technology is being developed by industry. Of critical importance in the development of large-scale data fusion systems is the standards and protocols that will allow distributed processing technology to grow.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Ongoing international research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Enhanced man/machine interface
- Rapid assimilation and processing of large data sets
- Data fusion algorithms for real-time analysis of large data sets
- Real-time operating systems for secure distributed processing
- Intelligent data extraction from text and pattern recognition (including application of neural nets).

In addition, detailed characterization and modeling of targets and sensor responses, propagation, and noise phenomena (see signal processing and weapon systems environment) will be key elements.

The table below provides a summary comparison of US and other nations for selected key aspects of technology that supports the data fusion process. Principal cooperative opportunities will exist with NATO countries, especially in technologies coming out of the European Strategic Program for Research in Information Technology (ESPRIT) program.

Summary Comparison--Data Fusion

Selected Examples	USSR	NATO Allies	Japan	Others
Enhanced man/machine interface, rapid assimilation and processing of large data sets	▨	□□□	□□□	
Data fusion algorithms for real-time analysis of large data sets	▨▨	□□	□□	□□ Israel
Real-time OS for secure distributed processing	▨	□□□	□□	
Intelligent data extraction from text; pattern recognition (including application of neural nets)	▨▨	□□	□□□	
Overall [a]	▨	□□	□□	□□ Israel

[a] The overall evaluation is a subjective assessment of the overall standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

US technology for software-based systems is far ahead of that of potential adversaries. However, the USSR's strong commitment to "radioelectronic combat" (electronic warfare) poses a challenge to US data fusion systems.

Japan has a substantial lead in display device and component research and development activities, and the United States is highly dependent on foreign sources for cockpit displays such as the F/A-18, AV-8B, and P-7 aircraft. This dependence could lead to a substantial erosion of the domestic industrial base in this technology and hinder development of further data fusion technological advances. Support through the Ministry of International Trade and Industry (MITI) and funding provided by a consortium of Japanese private companies that are interested in the development of high-definition television (HDTV) are primary drivers. These will contribute directly to enhancing man/machine interfaces for rapid assimilation of data.

2. Exchange Agreements

While data fusion as an isolated field of technology is not explicitly represented in the listing of international agreements surveyed, it is a pervasive subset of many other areas. The NATO Defence Research Groups (DRGs) in identification of submarines, defense applications of operations research, electronic warfare concepts and technology, and long-term research related to air defense all require, or will help to define requirements for, data fusion.

The Technology Cooperation Program (TTCP) provides a vehicle for exchanges in related areas of weapons, computers and software, applications of artificial intelligence, and other topics that form part of a viable supporting infrastructure for data fusion. In addition, TTCP activities include two topics--active aircraft control technology and data integration for undersea warfare--that are related to data fusion.

DoD is involved in an extensive cooperative program with the UK in the area of data fusion for strategic defense. The UK is especially interested in the development of parallel processing and artificial intelligence technologies to enhance data fusion capabilities.

Data fusion is a key element of a number of the Service weapon system-related exchanges. Service exchange agreements exist for definition of multi-function information distribution systems, cooperative communications, advanced attack helicopter mission equipment package, and cooperative measures to enhance sensor/multi-input intelligence data fusion. Similarly, advanced flight control concepts, aircraft mission equipment and main battle tank and naval tactical data systems/combat management will entail real-time fusion of inputs from large numbers of sensors and control feedback mechanisms distributed throughout the platforms, as well as the integration of such data with information from external resources.

13. COMPUTATIONAL FLUID DYNAMICS

A. DESCRIPTION OF TECHNOLOGY

Computational fluid dynamics (CFD) encompasses calculation of the fluid flow around bodies for all speed regimes and in any type of fluid--gas, liquid, or even solid (under special circumstances). CFD is beset by the fact that man's ability to write the governing equations of motion greatly surpasses his ability to solve them. The basic formulations known as the Navier-Stokes equations were first derived in 1827. These equations are enormously complicated since they must resolve the ever-changing flow within a turbulent fluid. Under the assumption that the fluid is a continuous medium, the Navier-Stokes equations are considered to be exact and to apply to even the smallest observable eddies of turbulence. If turbulent flow is considered, however, the governing equations are three-dimensional and unsteady. Moreover, the primary equations are three-dimensional, nonlinear partial differential equations in four independent variables; time is the fourth variable, because the flow at any point is always unsteady. At conditions where the continuum assumption no longer applies, such as at high altitude and high velocities, the chemical constituents of the fluid must also be included in the calculations. Because of these complexities, the governing equations cannot be explicitly solved from first principles using state-of-the-art supercomputers, except for the simplest cases. The result is that currently all solutions of the equations require application of considerable simplifying assumptions. Foremost among these is the elimination of the turbulence and viscous stress terms; the equations are then known as the Euler equations. Additional simplifications include mathematical modeling of the laminar and turbulence shear stress tensor, and restricting the degrees of freedom.

The technology is being developed and used to calculate fluid flow past or through bodies of interest to each of the Services and DoE to develop improved flight vehicles, ocean vehicles, air-breathing engines, and weapons. For conventional systems, such calculations greatly reduce both development cost and time. For most concepts designed to operate at speeds above Mach 8, CFD is the only way to determine the forces, moments, and heating of the vehicle. Overarching all of CFD technology is the problem of validation of the codes, recognizing that even the most complex codes are still only approximations. This requires carefully conducted experimental procedures. Validation for conditions where experimental data cannot be obtained is a serious concern.

Other key CFD development problems are in the areas of turbulence modeling, three-dimensional grid generation, and solution methodology from a software perspective. Secondary development problems involve algorithm development, complex geometry definition, and pre- and post-data processing. From a hardware perspective, mainframe computer methodology and architecture also warrant advances.

This critical technology will become a design tool, much like the wind tunnel, to increase the performance and effectiveness of aircraft, missiles, and hypersonic vehicles.

CFD can be applied to a wide spectrum of concepts such as aircraft maneuvering aerodynamics, airframe-propulsion and weapons integration, rocket and turbine engine propulsion, and conventional and high-energy weapons. Coupled with other disciplines such as structures, trajectory flight dynamics, optics, and electromagnetics, CFD can revolutionize the design process for flight vehicles, exploring design space well beyond that offered by conventional design methods. In addition, there are major applications in the design of submarines and ocean vehicles, specialized high-performance parachute systems, and folding aerostructures that will provide new targeting and surveillance capabilities for forward-deployed forces. This technology is also important for improved propellants for missiles and guns and superior gun-launched projectiles and missiles.

Critical Technology Challenges for Computational Fluid Dynamics

- Validation of CFD codes
- Unsteady aerodynamics
- Submarine design
- High-performance rotorcraft
- Hypersonic flight
- Propulsion system internal flows
- Interdisciplinary CFD

B. PAYOFF

1. Impact on Future Weapon Systems

CFD will lower design risks (accelerate development) and lower costs of all future flight vehicles that currently cannot be tested in restrictive flight regimes. CFD will be used to rapidly identify promising design concepts before wind tunnel tests are conducted, thereby significantly reducing system development time. Current wind tunnels cannot test even modestly sized full-scale aircraft at speeds above about 200 mph (Mach 0.2), or vastly reduced scale models at speeds above Mach 8. CFD will be used to design and evaluate higher speed vehicles such as hypersonic interceptors, reentry vehicles, hypersonic missiles, and low-cost expendable rockets. This technology can be applied to all classes of aircraft and missiles to improve performance and mission effectiveness. CFD will be used to address a wide variety of problems for current and future aircraft and helicopters, including airframe/propulsion integration, airframe/weapon integration and separation, aerodynamic/aeroelastic structure interactions, aeroacoustic/ structural interactions, and signatures.

Critical enabling technologies for the National Aerospace Plane (NASP) are CFD; lightweight, high-strength, high-temperature materials; and propulsion. The ability to accurately predict pressures and heating in flight and the propulsion system performance is vital to the development of the NASP vehicle. Based on the maturity of these technologies, a decision will be made early in FY93, on whether to proceed to develop the X-30 flight vehicle for flight tests in the latter part of the decade. From the lessons of the X-30 program, follow-on vehicles with true operational usefulness can be designed, which will make access to space more routine and less costly. In addition, these NASP-derived vehicles will be able to perform military missions within the atmosphere at greater distances and at speeds much faster than today's airplanes.

Overall, CFD, with advances in computer hardware architecture, will provide design tools for surface ships and submarines to support quieter, more stable, and more maneuverable operations and make wide spectrum signature treatment possible. CFD will also be used for submarine and surface ship design to minimize expensive model testing and to provide the capability to quickly bring a concept to full-scale application.

Improved rotorcraft aerodynamics prediction made possible by CFD will enable the design of smaller, quieter, more survivable designs with low vibration levels, thereby reducing crew fatigue and improving weapons accuracy and component lives. More agile and maneuverable rotorcraft will enhance the ability to fight and survive in air and ground attack in the nap-of-the-earth environment.

CFD has recently begun to be applied to the analysis and design of high-performance parachutes. Parachutes are thought of principally for aircrew survival and airborne assault; however, they also are important components on a variety of advanced weapons, as well as in the recovery, evaluation, and reuse of expensive weapon systems, research vehicles, and instrumentation during flight tests. Within the past few years, parachutes were deployed at over twice the speed of sound, recovered payloads weighing up to 170,000 pounds, and successfully delivered simulated weapon systems from aircraft flying only 100 feet above the target.

Flight vehicles operating at very low speeds present unique flow problems, which are readily addressed by the application of CFD. Such applications have led to the development of low Reynolds number folding aerostructures that can provide new surveillance and targeting capabilities for both surface and undersea vessels, enabling them to perform missions not now feasible.

For the ground forces, longer range artillery will provide a new capability in deep attack. Higher muzzle velocities will significantly affect anti-armor measures. Greater accuracy for gun-launched projectiles and missiles through better design is a major force multiplier.

2. Potential Benefits to Industrial Base

The United States currently has a commanding lead in CFD. However, this technology is recognized worldwide as an important technology, and strenuous efforts are being made in Japan and Europe to develop a competitive capability. CFD has proved to be a powerful tool for the US aerospace industry for design modification and problem solving, and its use for the design of the next-generation of commercial aircraft is expected to help continue the current dominance of US companies in the industry.

Costly development and test time savings can be achieved by innovative advances in three-dimensional large eddy turbulent simulations for advanced civil vertical take-off and landing (VTOL) and short take-off and landing (STOL) configurations including aeroelastic rotating blade and turbine flow field influences plus ground effects. Compressible CFD techniques with finite-rate chemical kinetics and multi-component diffusion need to be developed for applications including hypersonic aircraft propulsion and integrated full-scale aircraft designs. The full three-dimensional fluid/solid surface turbulence interaction process calls for sophisticated advances in CFD to provide accurate aeroelastic information for advanced materials and configuration designs for high-speed flight, as well as to address the illusive aerodynamic problems associated with boundary layer flow separation and laminar to turbulent transition on lifting airfoil surfaces.

Another effect of CFD will be on the fluid dynamic and mass transfer analysis of manufacturing processing flows, such as the production of silicon wafers from codes using chemical vapor deposition in chip fabrication and in casting and coating machine parts. Studies have recently shown that small changes in the fluid dynamics can cause a significant change in quality and performance in the production of silicon wafers. CFD technology is now mature enough to predict the deposition process in both continuum and non-continuum (very low density) conditions so that design improvements in chip production equipment can be made.

Another area in which CFD can have a significant effect is the dynamic simulation of high-temperature, gas deposited coatings on materials, and welding, soldering, and casting of high-temperature metals. These manufacturing processes have important application to the production of circuit boards, machine tools, electrical components, gas turbine parts, and other components suitable for high-temperature or corrosive environments.

C. S&T PROGRAMS

1. Milestones

Milestones--Computational Fluid Dynamics

Technical Area	By 1995	By 2000	By 2005
Computational techniques	• Moving grid solver • Hypersonic weapons separation codes • CFD vehicle structure codes	• Real gas/ionization effects • Inverse methods that design rather than evaluate configuration	• Intercisciplinary inverse design methods
Hypersonic vehicles	• NASP • Hypersonic air-breathing missiles	• Hypersonic inter-ceptors • Highly maneuverable reentry vehicles	• Low IR signatures • Hypersonic missiles • NASP-derived vehicles
Ocean vehicles	• 3-D Navier-Stokes for submarine applications	• Navier-Stokes for hydro-acoustic design of propulsors	• Inverse design with Navier-Stokes
Low Reynolds number vehicles (low speed flight)		• Complete demonstra-tion vehicles	• Submarine-launched targeting and surveil-lance vehicle • Ship-launched decoy and jamming vehicles • Ship-launched high-altitude long-range reconnaissance vehicle
High-performance rotorcraft	• Validated Navier-Stokes computations of advanced rotor systems	• CFD simulations of new rotorcraft concepts	• Highly maneuverable high-speed rotorcraft
High-performance parachutes	• Complete vortex panel models for predicting parachute flow fields • Develop and validate semi-empirical para-chute inflation codes • Extend decelerator technology into the hypersonic regime	• Place in operation an unsteady aerodynamic ground test facility for simulating parachute aerodynamics • Crew escape and para-trooper parachute systems with config-urations with greater reliability, and lower cost	• Complete development and validation of a full three-dimensional Navier-Stokes computer simulation of parachute inflation

2. Developing the Technology

Efforts continue to develop a CFD technology for the development of aircraft, hypersonic flight vehicles, air-breathing and rocket propulsion systems, and conventional and high-energy weapon systems. Improvements to existing methods and the development of more efficient new methods will provide the capability to address aerodynamic problems associated with high angle-of-attack maneuvering, weapon separation, acoustics, and airframe propulsion integration. CFD will become interdisciplinary and include structures, vehicle dynamic motion, flight controls, and electromagnetics. These capabilities will provide an integrated approach to flight vehicle design. A validated real gas CFD capability is essential for addressing surface cooling, ablation interactions, and complex aerothermodynamic interactions for hypersonic flight vehicles. Interdisciplinary CFD efforts for this speed regime will also address structural interactions, airframe-propulsion integration, optic physics, and infrared observables. For turbine engines, CFD methods will be available for calculation of unsteady internal engine flows to improve component efficiency and stability and to develop aircraft/engine thermal management schemes. CFD for rocket engines is focusing on the simulation of the internal engine flows for improving combustor performance; stability for liquid fuel rockets and gain deformation and aeroelasticity effects for solid fuel rockets and developing infrared/ultraviolet signature models; and plume analysis models for assessment of missile characteristics. The emerging capabilities, particularly those that integrate CFD with other disciplines, will enable major improvements in flight vehicle and weapon system performance and capability. Significant improvements in turbulence modeling and supercomputer efficiency, through advanced computer architectures such as parallel processing, are required to achieve this level of capability.

Many operational limitations of helicopters are due to unsteady flow separation and complex aeroelastic interactions produced by the tip vortices of the rotating blades. Advanced CFD techniques, coupled with new structural dynamics methodology, will allow the nonlinear aerodynamic phenomena to be simulated so that optimal rotor/body combinations can be analyzed and refined.

A primary goal of parachute technology development is to understand the complex unsteady fluid mechanics of a modern inflating parachute, beginning with its extraction from its deployment bag and continuing through parachute inflation. No other field of aerodynamics encounters such fundamentally coupled fluid/structural phenomena in unsteady aerodynamics. Modern weapon parachute systems operate exclusively in the unsteady aerodynamic regime; most hit the ground before they reach a condition of steady aerodynamics. Development of unsteady parachute aerodynamics technology is a prerequisite for meeting modern weapon design requirements.

Historically, CFD has concentrated on external aerodynamics with insufficient emphasis on complex chemically reacting flow. However, encouraged by the success of CFD, activity in simulating complex chemically reacting flows has increased substantially. However, our ability to predict complex reacting flows is at its infancy, and significant challenges exist in developing practical computational approaches. Once adequate treatment of complex multi-component chemical reaction is included (often hundreds of reactions are needed), the mathematical problems are both very much larger and significantly more nonlinear. Consequently, advances from numerical mathematics, in particular successful research on fast iterative algorithms, such as multi-grid or preconditioned conjugate gradient methods, will be essential to the successful development and application of CFD for chemically reacting flow.

Estimated funding[12] for developing this technology is as follows.

Funding--Computational Fluid Dynamics ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
420	80	80	90	90	90	90

3. Utilizing the Technology

CFD is being utilized for improving and extending our current aircraft capability, for operating wind tunnel test facilities more efficiently, to support flight test operations and flight safety, and in technology development. Airframe and propulsion integration efforts are underway to develop high-performance inlet and exhaust nozzle concepts to incorporate STOL, high-agility, and supersonic cruise capabilities into low observable aircraft designs. Vortex flow control concepts are being explored to increase the agility and control of aircraft at high angles of attack. Design data are being developed that are critical for the integration of high-performance inlets and nozzles into Mach 4 to 6 aircraft. CFD has been identified as a critical technology for the NASP flight vehicle. A thorough understanding of aeroheating phenomena is required for high-speed flight vehicles to build efficient structures that can survive the extreme temperature environments. CFD has been used in the Advanced Tactical Fighter (ATF) and B-2 development programs for configuration development and airframe-propulsion integra 'on. Wind tunnels are being enhanced to produce more accurate data for the validation of CFD codes. Key areas of research include low-turbulence, high Reynolds number wind tunnels, hot-wire anemometry, and laser velocimetry. Future uses of CFD will include weapons separation, acoustics, signature control, flight path dynamics, and propulsion system simulation. These capabilities are directed at achieving the vision of an interdisciplinary inverse CFD capability where the desired characteristics are specified.

Advances in supercomputers and computational techniques will enable aerodynamic and aeroelastic calculations of complete rotorcraft to be realized before the turn of the century. This revolutionary capability, which has already been demonstrated for fixed-wing aircraft, will lead to major improvements in rotorcraft by providing better and less costly design tools; reducing risks for new configurations; enhancing performance, efficiency, and aeroelastic stability; and reducing vibrations and noise.

Current hydrodynamics activity includes the development of three-dimensional Navier-Stokes codes for submarine design. Drag reduction work on ocean vehicles is expected to produce results that can be incorporated into an advanced technology demonstration in the 1990-95 timeframe. This technology will be able to support engineering development of submarines between 1995 and 2000. CFD technology is

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12 Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

expected to be incorporated in new ships beginning about 2010, when replacement of a large portion of the current fleet must begin.

Conversion of our understanding about unsteady parachute aerodynamics into parachute design and performance prediction codes is the next step in parachute technology development. Computer hardware and computational methods have progressed to the extent where numerical modeling of parachute inflation is feasible. Such feasibility is critical, as flight test costs have escalated to the extent that design-by-test is unaffordable.

DoD has unmanned autonomous vehicle programs that support the folding aero-structures development. This technology will be used by a joint acquisition program. By the mid-1990s, engineering development could be undertaken for three implementations: a submarine-launched target-acquisition and surveillance system, an off-board deception and jamming UAV to counter radio frequency and infrared (IR) anti-ship missiles, and a high altitude reconnaissance vehicle for long-range surveillance and warning for fleet air defense.

DoD's gun-launched projectile and missile programs include studies of supersonic and hypersonic flow past finned projectiles, base flow phenomena, transonic/supersonic flow transition, and flutter divergence boundaries for supersonic missiles. In ballistics, fluid dynamics is key to the development of improved solid propellant guns. Propellants themselves are being investigated to determine optimal grain configurations based on control of propellant fracture, improved ignition systems, and associated traveling wave charge phenomena. A related part of this effort is also directed to such requirements as control of muzzle blast and flashes.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

From the industrial base and manufacturing viewpoint, CFD includes the application software and the high-speed processing required to run the software, both hardware and operating systems. The industrial base issues lie in the computing platforms necessary for CFD. The current platform is the supercomputer, although the development of parallel processing architectures may supplant the supercomputer. (See the sections on semiconductor materials and microelectronics circuits and parallel computer architectures for an assessment of current supercomputer capabilities.)

2. Projected Manufacturing Capabilities

The major manufacturing capability derived from CFD is the development of more capable scientific computers. (See the sections on semiconductor materials and microelectronic materials and parallel computer architectures for planned manufacturing capabilities in this area.)

E. RELATED R&D IN THE UNITED STATES

While some CFD applications (such as hypersonic missiles) are unique to DoD, others (such as aircraft design) have both military and commercial applications, and are supported by NASA and industry. Computational fluid dynamics programs are also extensive in DoE and many universities.

The university community has played an especially active and productive role in CFD research with sponsorship by all three Services, the Defense Advanced Research Projects Agency (DARPA), the Strategic Defense Initiative Office (SDIO), NASA, DoE, the National Science Foundation (NSF), and others. This capability and knowledge has enormous potential for contributing to advancements in military aircraft, missiles, projectiles, ships, submarines, propulsion, and engines. The field is rapidly advancing and, as supercomputers become more widely available, this trend is expected to accelerate.

The US helicopter industry has been slower to utilize CFD technology than the fixed-wing airframe and propulsion communities, but a concerted effort led by DoD and NASA will accelerate the flow of this dramatic new capability for improving rotary-wing air mobility and weapons systems.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Improved abilities to apply CFD to complex three-dimensional aerothermodynamic analyses (including characterization of chemical reactions)
- Empirically validated codes for three-dimensional analysis of material response to high- strain/high-deformation rates
- Development of algorithms and programming tools to exploit massively parallel computing architectures.

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology. The United States is presently the leader in CFD. Cooperative opportunities will exist with NATO countries, especially in the area of specific algorithm developments. Further, if European nations proceed with development of several different aerospace plane concepts, provide further opportunities for cooperation will become available.

Secondary opportunities for cooperation in niche technologies may be realized in a number of countries, including Sweden, Italy, and Israel.

The major European countries have had considerable success in the practical exploitation of CFD. It has been used extensively in Europe to develop better designs for new transport and business jets and jet trainers. This capability for exploiting CFD is with comparable to methods in the United States. Our European allies have both the expertise in numerical methods and the most powerful US computers.

Summary Comparison--Computational Fluid Dynamics

Selected Examples	USSR	NATO Allies	Japan	Others
To improve abilities to apply CFD to complex 3-D aerothermodynamic analyses (including characterization of chemical reactions.	▨	☐☐	☐☐	
Empirically validated codes for 3-D analysis material response to high- strain/high-deformation rates	▨	☐☐	☐☐	
Development of algorithms and programming tools to exploit massively parallel computing architectures	▨	☐☐	☐☐	☐☐ Sweden, Israel ☐ India, China, Australia
Overall [a]	▨	☐☐	☐☐	☐☐ Sweden, Israel ☐ India, China, Australia

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	☐☐☐☐	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	☐☐☐	capable of making major contributions
▨▨	generally lagging except in some areas	☐☐	capable of making some contributions
▨	lagging in all important aspects	☐	unlikely to have any immediate contribution

Much of the basic scientific knowledge related to CFD is known to our allies. The UK is considered to have the greatest experience in applying this knowledge to weapon systems, but the FRG, Italy, and France are also assessed to have strong CFD capabilities. The ability of our allies to advance the field of CFD is expected to dramatically improve during the 1990s as the number of supercomputers and the research and development directed toward European involvement with aerospace planes (e.g., the Sangar) increase.

Knowledge of sophisticated algorithms, as well as the methods for practical exploitation of CFD, is widespread within NATO. France is the pioneer in finite element methods for complex aircraft configurations and is a leader in CFD development for turbulent simulations and modeling. The UK has efficient methods for transonic flow.

Germany is pioneering computations with the full Navier-Stokes equations and is applying them to analysis of hypersonic flight. The Netherlands has an extensive effort in developing algorithms for parallel processing, which also could contribute significantly. Italy is also contributing to the state of the art in CFD.

Japan has supercomputers and has, through research in such programs as their aerospace plane, begun to develop the validated data bases and sophisticated algorithms required to master CFD. Most countries outside of NATO and Japan lack access to large supercomputers to run their computations; however, a number are involved in the development of efficient algorithms.

For example, Sweden is involved in the development of large-scale algorithms. According to some CFD experts, the United States has greatly benefited from these developments. However, Sweden lacks the expertise in large data base management and the data bases themselves to be able to apply CFD technology to state-of-the-art military problems.

Israel has been a pioneer in developing efficient multi-grid methods for a variety of flows but is also limited by the same problems as Sweden.

China and India have shown interest in CFD, and their capability is growing. All of these countries have traditions of excellence in applied mathematics and fully participate in the science of numerical computation methods. Some capability has also been reported in Australia, but at the present the capability level for this country is unknown.

The Soviet Union and other potential adversaries are believed to be behind the US in this technology, with the exception of algorithm development, and are unlikely to close the gap in the foreseeable future because of US superiority in computers, software, and materials. However, the Soviets have a tradition of excellence in mathematical numerical methods. They have been able to keep pace with the United States in areas such as the space program, even with the serious lack of computer power. In CFD, the Soviets have pioneered fractional step methods. Their scientific literature seems to indicate that due to the lack of computational power, Soviet scientists and mathematicians are emphasizing efficient calculation methods. This could provide a knowledge base for development of efficient algorithms in the future.

2. Exchange Agreements

Formal exchange in CFD is limited, at least in part, by the nature of the field itself. Much of the underlying research into numerical techniques and algorithms takes place in an open academic environment. Practical applications, however (many of the most interesting codes--those that have been empirically validated), are proprietary.

While the Technology Cooperation Program (TTCP) does not appear to have an explicit exchange in CFD, it does provide a number of other mechanisms relating to aircraft control, through which transfers might occur.

The Air Force is the primary proponent for exchanges directly relating to CFD. It has agreements with several of our NATO allies in key areas, and there may be indirect return in this area from a broader international exchange program in computational techniques. In addition, CFD will benefit at least indirectly from many of the exchange programs in propulsion and materials (identified in other sections this plan).

14. AIR-BREATHING PROPULSION

A. DESCRIPTION OF TECHNOLOGY

A dramatic leap in aircraft propulsion capability occurred in the 1940s and 1950s with the introduction and rapid evolution of the gas-turbine engine, and substantial improvements have been made since then. Today, technological barriers in aerothermodynamics, materials, and structural design again can be broken, and another rapid evolution of propulsion system performance is impending. This rapid evolution will have a tremendous effect on the capability of DoD weapons and platforms and will have extensive dual-use applications in the US industrial base, which justifies its selection as a critical technology.

Generic air-breathing propulsion technology has application to a wide range of military systems, including aircraft, cruise missiles, future hypersonic systems, land combat vehicles, and ships. Types of propulsion systems involved include those based on gas-turbine, ramjet, and diesel engines. A broad and well-balanced science and technology effort, encompassing aerothermodynamics, structures, tribology, instrumentation, and controls is required to support military requirements.

Within this effort a specific example of a critical technology program, is the Integrated High-Performance Turbine Technology (IHPTET) program. This program is aimed at doubling aircraft gas-turbine propulsion system capability by the turn of the century. The general path to achieving this goal is well known. High temperatures at combustion initiation are required to increase efficiency (or decrease specific fuel consumption) and expand the flight envelope; higher maximum temperatures are required to increase the output per unit airflow; less weight per unit airflow is required to increase the output per unit weight; and all of the preceding requirements must be accomplished while maintaining or increasing internal component efficiencies. Specific technology developments required include increased aerothermodynamic capability for component efficiency levels and the control of heat transfer; high-temperature, light-weight materials (higher temperature aluminum and organic matrix composites, titanium and titanium aluminide composites) for the components upstream of combustion initiation; high-temperature materials (ceramic matrix composites, carbon/carbon, intermetallic alloys) for components downstream of combustion; and innovative structural arrangements. All of these developments must be accomplished in an integrated manner for each of the major component areas and for engine configurations as a whole. Critical component and manufacturing process technology thrusts for air-breathing propulsion are listed in the following table.

Critical Technology Challenges for Air-Breathing Propulsion

- Aerothermodynamics
- High-temperature and light-weight materials and coatings
- Light-weight structural design
- High-pressure ratio compression systems
- High-temperature combustors and turbines
- Reduced signature, multi-functional nozzles

B. PAYOFF

1. Impact on Future Weapon Systems

Aircraft gas-turbine technology is pervasive and critical to all current and future air-breathing weapons systems. The size, performance, mission capability, and life cycle cost of aircraft and cruise missile systems are directly dependent on the performance of the propulsion system--as evidenced by the fact that the propulsion system (engines plus fuel) accounts for 40 to 60 percent of the take-off gross weight for previous, current, and developmental aircraft. Given that aircraft-related expenditures in DoD account for roughly one-third of the budget, achieving the IHPTET goals will significantly affect future military capability. Accordingly, IHPTET is the highest priority effort in air-breathing propulsion technology. Some specific IHPTET goals and illustrative payoffs are given in the following table.

Goals and Payoffs--Air-Breathing Propulsion

Engine	Goals	Payoffs
Fighter	• 100% increase in thrust-weight ratio • 50% decrease in fuel consumption	• Sustained Mach 3 + capability • Supersonic V/STOL aircraft • 100% increase in range/loiter/payload over F-14
Rotorcraft	• 30% decrease in fuel consumption • 100% increase in power/weight ratio	• 100% increase in range and payload over CH-7
Cruise missile	• 40% decrease in specific fuel consumption 100% increase in thrust/unit airflow	• Intercontinental range cruise missiles in size of ALCM • High-speed capability • Low cost
Commercial/ transport	• 30% decrease in fuel consumption	• Increased range and payload • Longer life, reduced life cycle costs • Reduced parts count, improved maintainability

Hypersonic air-breathing propulsion (primarily scramjet) technology has the potential to extend military missions to new flight regimes and, through the National Aero-space Plane (NASP) program, to provide more economical and timely access to space. Hypersonic aircraft have the potential to enhance military capability to make high-speed intercepts and timely reconnaissance. Hypersonic air-breathing technology is the second highest priority effort in this area.

2. Potential Benefits to the Industrial Base

Aircraft gas-turbine technology is vital to the industrial base. The sales of domestic aircraft gas-turbine manufacturers were approximately $12.5 billion in 1988, equally divided between the military and commercial sectors. By virtue of the aircraft gas turbine's importance in determining the overall quality of aircraft, it is a major factor in the current favorable balance of trade in the aerospace sector, and the United States continues to be preeminent in this area. Because aircraft gas-turbine technology generally is equally applicable to military and civil engines, achieving the IHPTET goals will ensure continued US preeminence well into the 21st century. Further, aircraft gas-turbine technology is applied to ship propulsion, tank propulsion, and stationary power generating stations.

Hypersonic propulsion technology can apply to hypersonic transports, and the advanced materials and aerothermodynamic techniques required can be expected to contribute significantly to a wide spectrum of the industrial base.

C. S&T PROGRAMS

1. Milestones

At the core of the air-breathing propulsion program are the IHPTET efforts aimed at satisfying the fundamental performance needs of the aircraft gas-turbine engine. This program is structured in three time-phased steps, aimed at demonstrating technology in experimental engine configurations for three classes of engines: man-rated turbojet/turbofan, man-rated turboshaft/prop, and expendable engines for cruise missile or unmanned air vehicle applications. To achieve the overall demonstration goals, technology developments are needed in six major component areas: compression systems, combustors/augmenters, turbines, nozzles, controls, and mechanical systems. The milestones for these component developments, as well as the goals for the technology demonstrators, are shown in the table on the following page. The goals are referenced to the state of the art in 1987 and are to be achieved while maintaining current life and durability.

2. Developing the Technology

The IHPTET program is a coordinated effort among the Army, Navy, Air Force, DARPA, NASA, and industry. Plans have been developed for each of the six major component areas and the technology demonstrators, and are currently being executed. Each of the seven aircraft gas-turbine manufacturers have developed complementary plans in the same structure, and these are being executed with their discretionary resources. Because the development and design integration of advanced materials not previously available for use in turbine engines is a key to the successful achievement of the goals, these efforts are an integral part of the overall plan and are included in the funding.

Milestones--Air-Breathing Propulsion

Technical Area	By 1995 (Phase I)	By 2000 (Phase II)	By 2005 (Phase III)
Compression systems	• Metal matrix composites • Swept aerodynamics • 1300°F titanium/titanium aluminide • Hollow blades	• 1500°F titanium aluminide/MMC • Brush seals • Fiber-reinforced MMC • Ring rotors • 3-D viscous CFD design	• 1800°F titanium aluminide/MMC • All composite design • Exoskeletal structure • Max loading
Combustion systems	• Double dome/double wall liners • Transpiration cool augmenter liner • 2200°F ceramics • High-temperature augmenter flameholder spraybar	• Innovative dome concepts • CMC augmenter liner • 2800°F ceramics • Integrated augmenter/nozzle	• Variable geometry flow configuration • Integral design • Non-metallic liners • Titanium MMC cases
Turbines	• High-effectiveness cooling • 1850°F disk superalloy • High AN^2 rotors • Ceramic blade outer air seals • 2100°F thermal barrier coatings	• Improved cooling effectiveness • 3-D viscous CFD design • 2000°F intermetallics • Fiber-reinforced disk • 2500°F uncooled non-metallics	• 2800°F cooled non-metallics • 2500°F intermetallics • Greater than 3000°F uncooled non-metallics • Air leakage reduced 50% • Light-weight static structures
Exhaust nozzles	• Pitch vectoring • Composite liners • Selective cooling • 25-2800°F CC structures	• Pitch/yaw vectoring • Titanium aluminide MMC structures • Reduced cooling • 2800°F CMC panels	• Full vectoring • All-composite uncooled design • 1800°F titanium aluminide MMC • Greater than 2800°F CMC/CC
Control systems	• 600°F OMC/aluminum • 375°F electronics/optics • 375°F hydraulics/800°F EM actuators • IFPC logic/architecture • Adaptive fault-tolerant logic • VHSIC controller	• 750°F OMC/aluminum • 500°F electronics/optics • 500°F hydraulics/1000°F EM actuators • Advanced IFPC • Logic/architecture • Performance optimizing logic • Parallel process controller	• 900°F aluminum/MMC • 650°F electronics/optics • 600-700°F hydraulics/1200°F EM actuators • VMS logic/architecture • Reduced margin logic • Ultra-reliable controller
Mechanical systems	• 400°F liquid/600°F solid lube • Intershaft bearings/seals • Advanced dampers • 1000°F limited life bearing	• 600°F liquid lube • Advanced bearing/seal/gear materials • Advanced analytical tools • 1500°F limited life bearing	• 700-800°F liquid lube • Advanced component materials • Integrated mechanical system demonstration • High modulus shafting

(Continued)

Milestones--Air-Breathing Propulsion (Continued)

Technical Area	By 1995 (Phase I)	By 2000 (Phase II)	By 2005 (Phase III)
Technical Demonstrator (turbofan/ turbojet)	• +300% thrust/weight • +300°F maximum temperature • +100°F combination inlet temperature	• +60% thrust/weight • +600°F maximum temperature • +200°F combination inlet temperature	• +100% thrust/weight • +900°F maximum temperature • +400°F combination inlet temperature
Technical Demonstrator (turboshaft/ turboprop)	• -20% SFC • +40% power/weight • +300°F maximum temperature	• -30% SFC • +80% power/weight • +600°F maximum temperature	• -40% SFC • +120% power/weight • +1000°F maximum temperature
Technical Demonstrator (expandable engines)	• -20% SFC • +35% thrust/airflow • -30% cost • 1100°F combination inlet temperature	• -30% SFC • +70% thrust/airflow • -45% cost • 1200°F combination inlet temperature	• -40% SFC • +100% thrust/airflow • -60% cost • 1400°F combination inlet temperature

Basic research efforts sponsored by DoD and NASA at university and industry laboratories focus on the computation and measurement of fluid flow in future high-performance engines for a variety of applications. For example, basic research programs to measure the combustion processes with advanced laser techniques (Doppler anemometer for velocity, Raman scattering for chemistry temperature, Rayleigh scattering for density, laser-saturated fluorescence for hydroxyl radicals) are now underway.

DoD funding[13] for developing this technology is as follows:

Funding--Air-Breathing Propulsion ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
720	180	210	210	210	210	210

3. Utilizing the Technology

The three classes of technology demonstrators (turbojet/turbofan, turboshaft/prop, and expendable) serve two purposes. The first purpose is the evaluation of integrated behavior in a realistic engine environment. This evaluation is used to guide the further development of component technology.

The second purpose of the technology demonstrators is validating that the technology is sufficiently developed and understood to be transferred to new engine

[13] Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quality.

developments and to improvements of existing engines. The air-breathing propulsion program is structured so that these technology readiness demonstrations will be performed competitively in each of the three classes of demonstrators in each of the three phases. These demonstrations will ensure the timely availability of advanced technology for utilization in both existing and developmental engines (such as the engines for the advanced technology aircraft (ATA) and the advanced technology fighter (ATF) as well as any new engine developments. Since the technology ultimately is developed and demonstrated by the engine manufacturers, transferring it to both existing and new engines historically has been effective and timely, and the program has been structured to ensure that this process continues.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

Capabilities in the United States for manufacturing current production engines are excellent, with the possible exception of bearings. Current capabilities include the production of aluminum, titanium, and nickel- or cobalt-based superalloys, including the production of powders; hot isostatic pressing; hot isothermal forging; inertia welding; diffusion bonding; precision casting of air-cooled turbine parts in single-crystal, directionally solidified, or equiaxed forms; electrochemical and electrical discharge machining; electro-beam welding; laser drilling and welding; and all needed types of coatings.

2. Projected Manufacturing Capabilities

Achievement of the air-breathing propulsion goals will require that new manufacturing capabilities be developed. These new capabilities will include the manufacture of various fibers for composite materials with titanium, aluminum, titanium aluminide, ceramic, carbon, and intermetallic matrices; the manufacture of the associated composite materials in near-net-shape form; the production of rapidly solidified alloys; greater precision in the casting of air-cooled, single-crystal parts; and greater precision in machining methods.

Development of the needed processing capabilities on a laboratory scale is an integral part of the aircraft propulsion initiative, since developing the capability independently from the component to which it is to be applied is generally not possible. Engine manufacturers and materials suppliers participate, often jointly, in both DoD-sponsored and industry-sponsored programs to develop the needed processing activities. Subsequent to the development of these capabilities on a laboratory scale, manufacturing technology programs will be initiated to transfer the technology development efforts to needed production capabilities.

E. RELATED R&D IN THE UNITED STATES

Both NASA and industry participate in the coordinated IHPTET program. For FY91, related NASA funding is approximately $35 million, and related industry discretionary funding is estimated to be approximately $150 million. (DOD IHPTET funding is $115 million). Additional research activities for hypersonic propulsion is handled principally by NASA at its Langley, Ames, and Lewis Research Centers.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Although the two priority efforts in air-breathing propulsion, aircraft gas-turbine propulsion and hypersonic scramjet propulsion, are different in form, many key aspects of the technology are similar. Research and development in the following four areas indicate a potential capability to contribute to meeting the challenges and goals identified.

- Development and design integration of light-weight/high-temperature/high-strength materials
- Reduction of observables in high-temperature air-breathing propulsion systems
- Modeling and simulation (including CFD) of complex aerothermodynamic flow and empirically calibrated data bases
- Development of scramjet propulsion.

The table on the following page provides a summary comparison of US and other nations for selected aspects of the technology. With regard to the aircraft gas-turbine, the US continues to be the preeminent manufacturer, but less so than in the past, at least as measured by market share. Currently, the market share of US manufacturers is estimated at about 55 percent, down from a share in excess of 70 percent twenty years ago. In general, the US continues to lead in the key aspects of technology (it should be noted that the loss in market share is largely influenced by a 50/50 joint venture between a US and a French manufacturer for a commercial turbofan, in which the high-temperature part of the engine is manufactured in the US). Principal cooperative opportunities could exist with NATO countries (especially with France, the FRG, and the UK) and with Japan.

Other countries identified as having significant programs include Israel, Sweden, India, Taiwan, and the PRC. These programs are not, however, considered leading candidates to contribute to significant advances beyond existing NATO capabilities.

The infrastructure for gas turbine engines within NATO is highly developed. Increasing cooperation between the European Community nations (principally the UK, France, the FRG, and Italy) in aircraft engines should permit them to field a complete range of high technology aircraft engines for military applications.

France also is an important supplier of military and civil gas turbine engines. As noted, their high-thrust commercial turbofan engines are based on a 50 to 50 joint venture with a US manufacturer, in which the low-pressure components are made in France. In addition, France has emerged as a leading supplier of critical ceramic composites being investigated for potential future use in jet engine hot-section development. These are being evaluated in the US IHPTET program.

Summary Comparison--Air-Breathing Propulsion

Selected Examples	USSR	NATO Allies	Japan	Others
Development and design integration of light-weight/ high-temperature/high-strength materials	▨▨▨	□□□	□□□	
Reduction of observables in high temperature air-breathing propulsion systems	▨▨▨	□□□	□□□	
Modeling and simulation, and empirically calibrated data bases therefor	▨	□□	□□	
Development of Scramjet propulsion	▨▨▨	□□	□□	
Overall [a]	▨▨▨	□□□	□□	

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

Several nations are successfully producing, in whole or in part, serviceable jet engines, though they are not a source of competetive technology. These include the PRC and India, both of whom are successfully producing jet engines under foreign licenses.

Foreign activity in the area of supersonic combustion ramjets is not comparable to the US level of activity in the National Aero-Space Plane (NASP) program. Both Japan and Germany, however, have initiated hypersonic aircraft programs. The German program is eliciting interest from other NATO countries.

At the 1987 Paris Air Show the Soviets displayed a wind tunnel model of a Tupolev-designed Mach 5 scram-jet propelled air transport. US NASP experts have reviewed the design, which appears to be fundamentally sound. The USSR may, however, be hampered by limitations in supercomputing for computational fluid dynamics (CFD) and by large-scale production of critical composite materials.

2. Exchange Agreements

Formal exchange in air-breathing propulsion was found to be limited and primarily focused on advanced ramjet propulsion for weapons. This reflects, in large part, the nature of the international commercial infrastructure. This infrastructure is characterized by intense competition among firms that have already established international marketing and manufacturing relationships.

As a result primary interchange in this area occurs under Air Force data exchange agreements and Memorandums of Understanding (MOUs) with various NATO allies. The areas of exchange encompass technologies of materials and test techniques. Of specific note are the ties established with the French in ramjet-related and carbon material technologies; the French are considered world leaders in these areas.

In addition, the Navy has exchange programs with NATO allies in certain aspects of engine material and in marine gas-turbine propulsion. This area will benefit directly from many of the exchanges identified in the section on computational fluid dynamics.

15. PULSED POWER

A. DESCRIPTION OF TECHNOLOGY

Revolutionary changes in battlefield scenarios are possible because of major improvements in pulsed power technology that allow the development of high-power weapons and sensors. High-power weapon systems and sensors include directed energy weapons (DEW), kinetic energy weapons (KEW), improved target identification and surveillance systems, and rapid fire earth-to-orbit (ETO) launchers. DEWs (lasers, microwaves, and particle beams) provide speed-of-light operations with high firing rates at long ranges, which are capable of destroying or disabling missiles and other targets. KEWs utilize hypervelocity projectiles for long-range engagements, rapid fire rates, and deep magazines for anti-missile and anti-armor defense. In addition to directly powering battlefield systems, pulsed power technology is vital to assessing and simulating the vulnerability and lethality of present and future systems to nuclear, DEW, and KEW systems.

Critical component technologies for pulsed power systems are frequency energy storage, pulse forming (conditioning) networks (PFN), and coupling pulse to load (e.g., laser, high-power microwave tube). The prime power (generator, battery, etc.) delivers power to the energy storage subsystem, which transforms the energy in the pulse forming network to match the load requirements. High-pulse repetition frequency (PRF) energy storage subsystems require light-weight, high-efficiency, and compact energy storage with inductors and capacitors. Compact energy storage systems must have high energy densities (kJ/kg) to lessen military system weight. The PFN shapes the high-power pulse with capacitors, inductors, switches, and nonlinear elements and couples it to the load. Most systems require a high-power output switch between the PFN and the load.

Pulsed power energy storage systems often consist of enormous high-voltage, high-current capacitor banks that have compact modular design. High energy density capacitors with low inductance and fast current rise times are necessary for light weight and high repetition (up to 10 kHz) rates. Improvements in energy density between 1985 and 1989 reduced the mass of a 50 kJ capacitor by a factor of 10, from 150 kg to 15 kg. The increased energy density reduces the cost per joule, which makes advanced electromagnetic launchers feasible for launching payloads into earth orbit.

Two basic types of PFNs are important for pulsed power: inductive and capacitive energy storage. In the inductive energy storage system, the voltage stored in the capacitors discharges through an inductor/capacitor (PLC) network. Switches then isolate the energy in the inductive part of the PLC. In the capacitive energy storage system, however, the PLC network only shapes the output pulse, while the energy is switched directly to the load. Strategic defense applications using electromagnetic launchers require a tenfold improvement in inductive energy storage. High-pulsed power applications need improvements in gaseous and solid-state switch technologies.

Significant improvements are required in the switch technology for transferring the power from the PFN to the various weapon system loads. The switch must be designed to meet specific PRFs, sustained conductive time intervals, and rise-time and fall-time characteristics. The most important gaseous switches are spark gaps, ignitrons, and thyratrons. Gaseous switches require increased reliability, higher voltages, and greater current capacities to meet today's needs. Solid-state photo-conductive/semiconductor switches (PCSS) offer new alternatives: high powers, short pulses, light weight, and direct sources of precisely timed pulsed power. In conjunction with repetitive, high-density capacitors, PCSS switches provide low-cost, light-weight microwave sources for ultra-wideband radars, high-power microwave weapons and countermeasures, lasers, and particle beams.

Critical Technology Challenges for Pulsed Power

- Compact high-power sources
- Power conditioning
- Power switching

B. PAYOFF

1. Impact on Future Weapon Systems

Pulsed power is a critical element for the development of the following potential weapon systems: high-power microwaves, electrothermal and electromagnetic guns, neutral particle beams, space-based free electron lasers, ground-based lasers, and charged particle beams. Pulsed power is also essential for the development of other systems such as laser radars and ultra-wideband radars and nuclear weapon effect simulators. The table below shows the critical pulsed power parameters and the potential weapons likely to use that technology. A description of the most important weapon applications follows.

Critical Parameters in Pulsed Power

Pulse Power Components \ Pulse Power Applications	Electromagnetic launcher	Electrothermal launcher	Earth-to-orbit launcher	Ultra-wideband radar	Underwater acoustic sources	Nuclear weapon effects simulators	Laser radar	Neutral particle beams	Charged particle beams	Ground-based free electron laser	Space-based free electron laser	High-power microwave	Electromagnetic armor	Mine clearing
Capacitors	X	X	X		X	X	X		X			X	X	X
Voltage converters								X	X		X			
Pulse-forming networks		X		X	X	X	X		X			X	X	
Switches				X	X	X	X		X			X		
RF sources				X				X		X	X			

a. High-Power Microwaves

High power microwaves (HPM) provide a speed-of-light weapon or countermeasure that may cause mission abort for some kinds of systems or may prematurely set off explosive components in other kinds of systems. Narrow bandwidth systems are being developed for beamed weapon applications, and ultra-wide bandwidth systems are being developed for countermeasures. These weapons or countermeasures may temporarily confuse, blind, or upset important sensors; damage critical electronics so that they cannot function until physically replaced; and disable, disrupt, or upset electronic control circuits. Successful development requires advances in radio frequency (RF) power sources, pulsed-power conditioning, frequency or time coherence control, and antenna technology. Development is also necessary to improve system ruggedness, reliability, and repetition rate.

b. Electrothermal Guns

The Services have a need to develop electrothermal guns. The Army can use electrothermal guns as an extended range (3 to 5 km) anti-armor weapon that is lethal against the next generation of Soviet tanks. The Navy has an urgent need for a weapon that can be mounted in surface ships to intercept and destroy present and future missile systems at distances greater than 15 km. The Air Force can use electrothermal guns for close-air support aircraft, such as the A-10, to destroy armor on the ground at ranges of up to 5 km. The development of compact, mobile pulsed-power conditioning is the critical link to develop these weapons.

c. Electromagnetic Launchers

Electromagnetic launchers can be used for strategic applications as a terminal defense weapon to destroy oncoming missiles and in space platforms to destroy reentry vehicles. To develop these potential weapons, a significant advance in pulsed power is required. If an inductive energy storage system is used, multi-Hertz opening switches with PRFs of a few Hertz and conduction times of hundreds of microseconds are needed to use hundred Megajoule energy storage inductors. Using a capacitive energy storage system with a 0.5 to 5 MA closing switch (and a PRF of a few Hertz) requires a 2 to 5 millisecond conduction time. Electromagnetic launchers need a fivefold increase in capacitor energy storage density to launch large size masses into orbit.

d. Neutral Particle Beam

Neutral particle beam (NPB) systems are currently under development for strategic defense against missiles but are also effective for anti-satellite (ASAT) missions. A light ion beam is accelerated to energies higher than a Gigavolt (GeV) and neutralized before leaving the platform. At sufficiently high beam powers, the beam deeply penetrates into the target, damaging the electronics, detonating the high explosive within the reentry vehicles, and producing structural damage. Continuous wave ultra-high frequency (UHF) radio freguency (RF) sources are the most crucial pulsed power technology required to make NPB systems practicable.

e. Space-Based and Ground-Based Free Electron Lasers

Free electron laser (FEL) systems are under development by the Strategic Defense Initiative with potential applications for ground and space defense. For strategic defense applications, high-energy laser beams discriminate reentry vehicles from decoys and kill both booster and post-boost vehicle structures. ASAT weapons and ship-based anti-missile defense (ASMD) use FELs. A key pulsed-power conversion technology is the RF source required to drive the free electron beam.

f. Charged Particle Beam

Charged particle beam (CPB) systems are being considered for ship-based ASMD weapons and pop-up interactive discrimination of targets in strategic defense applications. An electron beam is accelerated by a repetitively pulsed induction type accelerator. Switching is the key pulsed-power technology for this application. Precision controlled switching is ideally suited for this application because of the rapid switching of high voltages at high peak powers. In addition, light-weight DC/DC inverters will be needed to transform the low DC voltage to the high DC voltage required by the primary energy storage capacitor and PFNs.

g. Ultra-Wideband Radars

Ultra-wideband (UWB) radars have three principal advantages: high-clutter detection (foliage, low altitude targets, etc.); low-cost target imaging; and real-time target identification. UWB radars require precise temporal control of a few tens of picoseconds to achieve coherent transmission and reception of high-peak power, UWB RF. Precision controlled switching with very low jitter (a few picoseconds) and extremely fast modulation rates is required for the development of these new types of radar waveforms. UWB radars have very high range resolutions, and the ultra-wide bandwidths simultaneously measure the low frequency (Rayleigh), the resonant and the high frequency (optical) signatures of a radar target.

2. Potential Benefits to Industrial Base

Significant spin-off of pulsed power and power conditioning technology to the commercial industrial base is already occurring. New commercial applications are resulting: the majority are in the electric utilities, electric drive and control industry, and the medical industry. Several examples of specific spin-off applications are described in the following paragraphs.

The DoD Mile Run energy storage capacitor development program (jointly sponsored by the Strategic Defense Initiative Office (SDIO) and the Defense Nuclear Agency) has achieved dramatic increases in energy density within the last few years. The use of molecular engineering techniques first synthesized polymer films specifically optimized for energy storage. The molecular engineering techniques synthesize new polymer films for ultra-reliable applications required by the heart defibrillator industry. High-energy density capacitor availability is making the pulsed metal forming industry more cost competitive. In fact, at least one automobile corporation is using this approach to affix end caps to driveshafts. The electric utility industry is interested in using high-energy density capacitors for power factor correction because they are installed on a utility line by a single technician. Significant cost reductions are among the development goals for pulsed-power accelerators, which also will help to reduce costs of commercial accelerators for medical applications.

Many high-power switch developments have been pursued by DoD, and several of these devices are being used in commercial applications. Hydrogen thyratron switches originally developed for the SDI ground-based laser are now used by a manufacturer of ultrasonic kidney stone break-up machines. Less mature, but more significant, is a new type of solid-state switch, the MOS Controlled Thyristor (MCT). The MCT is a high-power, efficient electric motor controller switch. The MCT makes possible automobile industry plans for the demonstration of front-wheel drive vehicles with electric motor drives for enhanced traction. The electric utility industry will use MCTs for future fault management switchgear and power processing units for DC-DC transmission lines.

Long-term development of high-power switches by the DoD will affect the competitive position of the United States by making compact, efficient, and agile power systems available. UWB pulsed-power technology will provide more efficient, agile, and versatile pulsed-power sources for narrow and wide bandwidth RF applications. Several companies are developing precision switching technologies to synthesize narrow and ultra-wideband RF pulses for radars and countermeasures.

C. S&T PROGRAMS

1. Milestones

Milestones--Pulsed Power

Technical Area	By 1995	By 2000	By 2005
High-energy density capacitors	• 10^4 J/kg at 1 Hz • 10^8 shots	• 10^4 J/kg at 10 Hz and 10^8 shots • 100 J/kg at 1000 Hz and 10^9 shots	• 10x improvement in energy density and shot lifetime
Switches • Magnetic • Solid-state • Plasma	• 100 kV at 10 kHz • 0.3 nsec risetime at 10 Hz • 10^{14} A/sec single shot	• 1 MV at 100 kHz • 0.1 nsec risetime at 10 kHz (50 MHz burst) • 10^{14} A/sec at 10 Hz	• 10x improvement in average power capability
High-power microwaves (1-3 GHz)	• 1000 J at 1 Hz	• 10 kJ at 10 Hz	• 100 kJ at 10 Hz
High-power RF devices	• 60 kW	• 500 kW	• 1.5 MW
Compact accelerators	• 20 MeV at 10 kA, single shot	• 500 MeV at 10 kA, and 10 Hz	
Inverters	• 500 g/kW	• 300 g/kW	• 100 g/kW
Alternators	• 100 g/kW	• 30 g/kW	• 10 g/kW
Fuel cells	• 700 g/kW	• 260 g/kW	
Batteries	• 16 watt-hr/kg	• 100 watt-hr/kg	
Voltage converters	• 1 kW/kg	• 30 kW/kg	• 10 kW/kg

2. Developing the Technology

High-energy density capacitors for rapid discharge applications have been developed by the Mile Run Program. Using molecular engineering techniques, designers are able to construct candidate molecular structures and evaluate their performance on a computer to achieve the highest performance. Prototypical devices are built from the new materials in the laboratory.

Molecular engineering techniques may be further refined and expanded to improve life time, reliability, and other parameters.

The development of high-power, gas discharge switches depends on the underlying plasma physics within the devices. New analytical tools to predict device performance as a function of electrode geometry and materials are required. Computer simulations of plasma operating conditions enable switch designers to improve gas discharge switch performance to new levels.

Solid-state power switches with low impurity substrate materials significantly increase power handling with the development of new device geometries and wafer-scale integrations of multiple devices on the same substrate. The United States is only beginning to produce the required low-impurity level gallium arsenide (GaAs) substrate materials and may have to continue to procure it off shore. The interconnection of multiple devices in parallel will permit significantly higher powers. On-chip computers control the power management of individual devices.

A summary of total S&T funding[14] is shown in the table below.

Funding--Pulsed Power ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
640	160	150	160	160	170	170

3. Utilizing the Technology

The importance of pulsed-power components and subsystems to critical DoD weapons, radars, and electronic warfare (EW) systems was recognized by the Joint Directors of Laboratories (JDL) by establishing a tri-Service pulsed-power team to assess US resources to high-energy, high-power programs for future military system requirements.

The development of advanced high-energy-density (HED) storage will affect both mobile and fixed applications. Cost studies indicate that a 50 to 250 kilogram satellite could be launched by an electromagnetic system into a low earth orbit for only 3 percent of the present launch costs. Launch on demand to low earth orbit for reconstituting satellite constellations or for almost real-time reconnaissance has significant military utility.

The Mile Run Program employs 50 kJ capacitors (discharge times of 10 to 100 microseconds) and has reduced the mass from 1,200 kg in 1970, to 150 kg in 1985, and to 15 kg in 1989. High PRF (up to 100 Hz) capacitors with lifetimes in excess of 10^8 shots support SDI applications in space, while the high-energy density capacitors have 1 Hz PRFs with 10^4 shot lifetimes, and support tactical applications.

Both the Army and the Navy have identified missions requiring electromagnetic (EM) launchers or electrothermal (ET) guns using order of magnitude improvements in energy density. An Army tank-mounted EM gun to penetrate advanced armor is needed as well as an extended range artillery piece for Army or Navy use.

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14 Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

Some new applications become practical with the development of advanced capacitor technology. Electrically driven surface-discharge acoustic sources would become practical for active submarine detection over large areas of the ocean. The payoff in this approach (over more conventional means) is the precise control of the acoustic waveshape to achieve optimal signal-to-noise ratio for detection at a given range.

High-voltage thyratron switches are required for HPM weapons, countermeasure systems, and ultra-wide bandwidth sensors. Thyratron switch output can be sharpened through nonlinear shock techniques to increase the bandwidth for radars and countermeasures.

Development of the high-power MCT enables efficient electric drive for Army tanks, integrated ship electric-drives, and long endurance aircraft drives. Laser radars and other sensors significantly benefit from MCT devices.

The development of advanced solid-state switches will be required for many types of RF radars and countermeasures. UWB radars, as a means for detecting low-altitude and low cross-section targets, may require optically triggered photo-conductive switches to be effective. Charged particle beam systems for ship defense and for interactive discrimination of re-entry vehicles from decoys also require the new switch technology.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

Manufacturing firms have no incentive to become involved in the low-volume pulsed-power market. Pulsed high-power for military applications continues to be needed for only applied and basic research efforts. For many years, pulsed high-power systems were only required by large one-of-a-kind facilities for weapons effects testing and fusion research. The manufacturing situation led to many small, research-oriented companies filling the requirements for limited quantities of pulsed-power components and hardware. Large companies supplied components to the military only as a sideline to their main commercial business. Solid-state switches and pulsed-power semiconductor devices formerly made in the United States now must be purchased overseas. The advent of modern high-energy beam weapons concepts such as high-power lasers, particle beam weapons, electromagnetic guns, and high-power microwaves, increased interest in pulsed power systems. Work on these devices is research-oriented, and major reductions in the size and weight of the associated power systems are required to field a system. In the current environment, the organizations supporting the military's pulse power programs are research or university oriented.

The manufacture of high-energy density capacitors depends on computer-controlled precision polymer-film winding machines, purchased from a foreign source. As larger devices are required, larger machines with precise torque control will be needed.

The ultimate power handling performance of solid-state switches depends on the impurity level in the semiconductor substrate. The Japanese have the world's leading ability to produce large GaAs wafers.

2. Projected Manufacturing Capabilities

The technology required to build pulsed-power systems that meet the size and weight requirements necessary for high-volume production is not available. Sufficient system definition and program direction may be available by 1995. The commercial power industry will provide little support because the rise times and pulse rates required for their systems are generally much less than those specified for military systems. Potential manufacturing technologies of interest include solid-state and gas discharge switches of the opening and closing type, inductive storage devices, capacitors, batteries, and homopolar generators and compensated alternators. Commercial activities are underway to efficiently synthesize RF signals (both narrow and wideband) from DC to RF. No producibility or reliability have yet been demonstrated for either radars or communications.

E. RELATED R&D IN THE UNITED STATES

For non-defense applications, an entire class of high-power accelerators with solid-state amplifiers with fast starting times exists. DoD development of RF power will have direct applications for nuclear particle physics; radioisotope production of medical isotopes; radiation therapy; materials, metals and plastics; ion implantation in semiconductors; neutron analyses (neutron radiography of luggage); and production of tritium for weapon applications. High-energy electron accelerators have additional applications such as radiation therapy, industrial radiography, sterilization of medical tools, food preservation, free-electron lasers and synchrotron light sources, and sludge and waste treatment. A potential application for future NASA missions might include high-power transmission of energy from ground to space or between space systems.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Pulsed-power conversion technology encompasses techniques for conversion, storage, pulse-forming, and transmission of electrical energy to power a variety of weapons (lasers, KEW, HPM, or particle beams) or high-powered radars and electronic countermeasures. Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Reduction in size of power systems and components by order of magnitude
- Development of photo-conductive, solid-state switch
- Development of HPM sources, including impulse radar.

The table on the following page provides a summary comparison of the United States and other nations in selected key areas of pulsed power. The United States is the undisputed free-world leader in the development of compact, light-weight power systems for a variety of applications. Recent breakthroughs in US capacitor fabrication (increasing energy densities by an order of magnitude) have established a significant US lead in this key niche technology. However, the Soviet Union has an extensive program in pulsed power and may lead in a number of other areas (e.g., pulsed magnetohydrodynamics).

Summary Comparison--Pulsed Power

Selected Examples	USSR	NATO Allies	Japan	Others
Reduce size of power systems and components by order of magnitude				
Development of photo-conductive solid-state switch				
Develop HPM sources, including impulse radar				
Overall [c]	[b]		[b]	[a] Various Countries

[a] The Soviets have developed a number of alternative technology approaches; overall, they are on a par with the United States.
[b] Strong in primary power sources that may prove adaptable to pulsed power systems.
[c] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States	Capability of others to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

Opportunities for cooperative research in pulsed power will generally be limited to NATO and Japan and will be primarily in niche technologies relating to switching or specific applications. In addition, there is potential for cooperation with NATO countries and Japan in a range of technologies that might be used as primary power for pulsed systems. Japan could make significant contributions in materials for photo-conductive switching.

The Soviet Union has developed high average power repetitive pulsed power technology that is more portable than the US equivalent. The Soviets are the current leaders in this field; in fact, they may well be in the lead in some key technology areas, particularly gaseous switching and inductive energy storage.

US government funding for pulsed-power R&D is divided among the national laboratories, private industry, and universities. The same is generally true internationally, except in Japan. There, in addition to government-funded R&D in pulsed-power, Japanese industry is funding several university programs for developing repetitive electron and ion beams for materials processing. Japanese GaAs technology might also have potential future uses in active array pulsed microwave power generation.

In the FRG, Soviet Union, the UK, and the PRC, pulsed-power research and development is exclusively funded by the government, with national laboratory and university components. Funding for military applications is generally level and increasing funding for commercial applications is increasing.

In pulsed-power-related fields, effective two-way exchanges exist. Although joint developments are very rare, initiatives from the Japanese, the Soviets, the Israelis, the British, and the Germans are planned or under way on a small scale.

Basic research results are exchanged in international forums. X-ray sources from the Soviet Union, basic experiments on ion beam treated surfaces from Japan and the Soviet Union, new materials from Japan, diagnostic and basic research on fundamental physics from the FRG and the Soviet Union, and new product designs and international meetings involving the Soviet Union, Japan, Germany, and other countries characterize multi-national exchanges. Exchanges are generally limited to basic research results and bulk materials needed for components.

2. Exchange Agreements

There is significant international exchange in basic research on inertially confined fusion and high energy physics. The Air Force has an exchange program in laser and RF systems with the UK; the Army has such a program in high-power microwaves. The SDI program has MOUs with several countries, under which interchange of pulsed-power technology is possible.

16. HYPERVELOCITY PROJECTILES

A. DESCRIPTION OF TECHNOLOGY

Hypervelocity projectile technology involves the capability to propel projectiles to greater-than-conventional velocities (over 2.0 km/sec), as well as understanding the behavior of projectiles and targets at such velocities. Propulsion systems that are being investigated include electromagnetic guns, electrothermal guns, traveling-charge guns with liquid or solid high-energy propellants, hypervelocity rockets, and explosively driven shock tubes. New designs of armor-piercing rod-shaped charges, explosively formed penetrators, and long-rod kinetic-energy projectiles are also being developed.

In designing hypervelocity projectiles external ballistics, such as the aerothermodynamic environment, control mechanisms, drag reduction, and impact and penetration of the targets, must be considered, as well as the interior ballistics associated with the actual launch mechanics of such projectiles. Critical technology challenges in hypervelocity projectiles are listed in the table below.

The highest priority thrusts for both tactical and strategic applications include development of launchers and associated propulsion systems, high-g miniature guided projectiles, characterization of projectile flight and stability in the atmosphere, pulsed high-power/compact-power supplies, high-energy density capacitor technology, homopolar generators, high-power density alternator technology, composite materials development, and superconductivity.

Critical Technology Challenges for Hypervelocity Projectiles

- Projectile design
- Projectile propulsion
- Projectile-target interaction

B. PAYOFF

At the tactical level, it is imperative that US antiarmor weapon technology keep pace with the new generation of armor fielded by potential adversaries. At this time, developments such as reactive armor have made it doubtful that the current antiarmor weapon inventory will be able to defeat the threat during a rapid enemy offensive.

Hypervelocity projectiles provide more penetrating and destructive capability, enhancing their effectiveness against simple, composite, and active armors.

The effective range of conventional unguided anti-aircraft projectiles is limited to several kilometers, since the targets can maneuver out of the line of fire during the projectile's time-of-flight. As compared to a standard gun-launched projectile, a hypervelocity projectile's time-of-flight to the target is significantly decreased, thereby increasing the weapon's effective range.

On a strategic or theater level, a ground-based hypervelocity gun (HVG) element can intercept re-entry vehicles (RVs) in their endo-atmospheric phase of flight, or it can be used for launching an exo-atmospheric projectile for a mid-course intercept. It has the advantage of a high rate of fire at a low cost per projectile, and high velocity, which permits multiple engagements of incoming RV, cruise-type missile, or compressed flight trajectory sub-launched targets.

At the strategic level, a space-based HVG platform provides a viable, cost-effective interim to laser weapons for boost phase intercepts of advanced threat intercontinental ballistic missiles (ICBMs). A boost phase intercept provides the highest measure of deterrence since it can eliminate all RVs being carried by the booster with one shot. Since an adversary cannot predict which RVs are eliminated, he cannot predict targeting results.

Finally, for inadvertent launches or short-range terrorist-type launches only one space-based platform would need to be activated, while many slower velocity space-based interceptors (SBIs) may need to be activated. Command and control is minimized at all times with HVG platforms.

By increasing the terminal effects per unit of projectile mass, hypervelocity weapons also offer a potential reduction in the overall systems' mission weight.

C. S&T PROGRAMS

1. Milestones

Milestones--Hypervelocity Projectiles

Technical Area	By 1995	By 2000	By 2005
Target Penetration			
• Rocket-boosted warhead	• Operational capability		
• SKEP	• Prototype warhead	• Product improvement	
• Energy-enhanced penetrator	• Application feasibility	• Prototype warhead	
• Programmable fuzing	• Feasibility demonstration	• Product improvement	
• HVG, ground-based intercept	• EMG testing • 15 kg shrouded LEAP (100 kg tolerance) • 1 kg LEAP (200 kg tolerance)	• Integrated testing • 2 km ground vacuum range tests	
• EM space launch system projectile	• Design 75 kg generic projectile • Test to 50 kg	• Launch to orbit 4.5 kg payloads	
Tactical HVG			
• Launcher	• 15 kg at 6.4 km/sec • 2,000 shot at 5 Hz	• Deployment	
• Power	• 7,000 MW for 200 sec	• Deployment	
• Fire control	• Full target tests	• Deployment	
• Systems	• Integrated mobility	• Deployment	
Terminal Defense HVG			
• Launcher	• 5 kg at 4 km/sec • 200 shots at 3 Hz • 38 m length • 10 tons	• Deployment	
• Power	• 500 MW for 60 sec	• Deployment	
• Fire control	• Radar targeting	• Deployment	
• Systems	• ISD	• Deployment	
Ground-Based Interceptor Systems			
• Launcher	• 15 kg at 6.4 km/sec • 2,000 shots at 5 Hz	• Integrated ground target	• Deployment
• Power	• 1,000 MW for 200 sec	• Integrated testing	• Deployment
• Fire control	• Final algorithm	• Integrated testing	• Deployment
• Systems	• Brassboard systems	• Testing	• Deployment

(Continued)

Milestones--Hypervelocity Projectiles (Continued)

Technical Area	By 1995	By 2000	By 2005
Space Defense HVC System			
• Launcher	• 2 kg at 10 km/sec • 750 shots at 2 Hz • 38 m length • 3.5 ton • 50% efficiency	• Integrated ground test	• Space tests
• Power	• 850 MW for 378 sec	• Ground test	• Space tests
• Fire control	• Brassboard system	• National testbed simulation	• Integrated tests
• Systems	• Brassboard	• Integrated tests	• Integrated tests
EM Space Launcher System			
• Launcher	• 75 kg at 5 km/sec	• 75 kg at 7 km/sec	• Deployed
• Power	• Utility grid	• Dedicated 500 MW utility grid	• Deployed
• Fire control	• Exercise automatic launch control and tracking	• On-orbit rendezvous	• Deployed
• System	• Conduct space mission with 20 kg payloads	• Test automated barrel refurb	
Induction Launchers	• 75 kg at 5 km/sec		
Plasma Mass Launchers	• 500 g at 15 km/sec		
Electrostatic Launcher	• 1 g at 50 km/sec	• 10 g at 100 km/sec	

2. Developing the Technology

For tactical use, both electromagnetic and electrothermal guns will require fieldable pulsed-power generators and pulse-forming networks with power beyond the current state of the art. (See the section on pulsed-power technology.) Efforts focused specifically on these guns include development of materials for rails, armatures, and electrodes that resist erosion due to the intense electric arcs; designs for rail guns that are light weight yet resist the strong electromagnetic forces; materials for rail gun armatures; and materials and designs for projectiles. Hypervelocity rocket research concentrates on propellants that meet the conflicting requirements of extremely high burning rates, low sensitivity, and low signature (flame and smoke). Explosively driven shock tube research is focused on a sophisticated method to design experimental systems to drive projectiles to 15 to 20 km/sec.

The penetration capability of long-rod kinetic-energy (i.e., hypervelocity) penetrators increases with their length-to-diameter ratio (L/D) and decreases with the parasitic weight of the sabot used for launch. This fact drives research to address the ability to produce very stiff, tough rods (which resist breakup during launch, flight, and impact) and low parasitic weight means to keep the rod stable during launch and flight, thus reducing bending stress.

The aim of one major DoD program is to test advanced kinetic-energy projectiles in a 9 Megajoule railgun; the program is carried out jointly by the Services and the Defense Advanced Research Projects Agency (DARPA). The program includes areas such as low-cost processing of ballistic ceramics; development of new alloys and processing methods for tungsten and depleted uranium; development of light-weight, high-strength cermets; fundamental investigations of the physical basis of armor penetration; computational penetration mechanics and improvements in modeling high-rate deformation and failure; and studies of the thermochemical processes in explosive detonation and deflagration/detonation transitions. DARPA also has a program for experimental evaluation of new armor/anti-armor technology.

A second major DoD program is within the Strategic Defense Initiative Office (SDIO). Advances are now close enough to existing SDIO requirements to permit more precise definitions of those requirements, as well as a more detailed look at program options.

Muzzle energies and barrel lifetimes have increased one hundred fold in the last five to seven years, while efficiencies have increased almost an order of magnitude. Firing rates have increased from daily to 20 Hz in the last three years. Efficiencies are already high enough for ground-based systems. Barrel lifetime and muzzle energies are within a few fold of requirements.

Power technology for HVG systems has achieved 10 to 100 fold increases in power and/or energy densities in the past five years. Cost-per-unit energy for fixed-site systems has been reduced 10 to 100 fold by utilizing advanced battery technology developed by US industry during the past decade. Existing technology makes fixed-site HVG power systems both feasible and economic. Another order-of-magnitude reduction in power supply mass and volume will enable mobile and space-based HVG systems. This development is commonly believed to be feasible in the near term given sufficient funding.

Projectile and fire control technologies likewise have made dramatic progress in recent years. SDIO has funded these programs heavily, and payoffs are now beginning to be seen. Although focused on applications other than HVG systems, these technologies can probably be applied to HVG systems. Complex guided interceptors now appear feasible with tenfold lower masses than a decade ago, and fire control solutions are possible given ongoing advances in concepts, software, and hardware.

One critical aspect of the SDIO projectile program has focused on the inertial measurement unit (IMU) and IMU components development. The IMU research and development programs include Interferometry Fiber Optic Gyro (IFOG), Rate Sensors, Resonant Fiber Optic Gyro (RFOG), and Quartz Gyros. Further research work is being programmed for developments in micro-optic gyros (MOG).

Additionally, fundamental research programs are looking at various IMU component technologies, including fully solid-state MOGs and cryogenic temperature operation of RFOGs.

The basic goals in the IMU programs are to reduce the size, weight, and cost of the IMU. Reductions in each of these goals offer significant payoffs in system performance for the Exo-atmospheric Re-entry Vehicle Interceptor System (ERIS), the high Endo-atmospheric Defense Interceptor (HEDI), the Space-Based Interceptor (SBI) or Brilliant Pebbles Interceptors, and the Extended Range Interceptor (ERINT), as well as the hypervelocity electromagnetic launched (EML) guided projectiles. Therefore, it is critical to continue efforts in this area.

The ongoing programs have provided significant accomplishments. The IFOG IMU provides inertial measurement in a 400-gram package with less than 1.3 degrees per hour drift. This can provide improved interceptor accuracy and reduced system hand-over accuracy requirements. The Quartz Rate Sensor IMU may provide 1 degree/hour drift and radiation hardening in a 70-gram package.

Fundamental research in solid-state MOGs has shown the feasibility for deposition of optical resonant rings on silicon substrates. Also investigated were various material compatibilities and techniques for building a gyro which ranged from lower risk partial solid state to higher risk fully solid state MOGs. The research in Cryo-RFOG has demonstrated that an ambient temperature RFOG could be reduced to a 10-gram version operating at cryogenic temperatures and mounted on the back of the seeker focal plane for synergistic use of the coolant as well as reduced parallax and bending errors.

Ground tests and flight tests are planned for the IFOG IMU and RFOG IMU. In FY91 and 92, ground tests, flight tests, and qualification tests are planned for the Quartz Rate Sensor IMU. A modest research program on the Cryo-RFOG should continue until FY93 when it will be ready for advanced development. Fundamental research in the solid state MOG was discontinued in FY89 due to funding constraints. However, because of the low production costs associated with a fully solid state IMU, a research effort should be restored in DoD in this area. Anticipated research programs for the next generation IMU include studies in fourth generation Ring Laser Gyros (RLG), solid state RLG, High Temperature Superconducting Gyros, and low cost non-planar RLGs.

Various SDIO HVG architecture studies have been completed in the past year and others begun in the last several months. Recent technological progress has made HVG systems seem much more viable for both tactical and SDI applications than might have been concluded as little as five years ago. The completed studies have produced technology assessments and system requirements against which ongoing and future program goals need to be assessed.

DoE's role in this technology is to support DoD development of advanced conventional munitions. The President's 1985 Blue Ribbon Task Group recommended broadening the traditional mission of the DOE nuclear weapon laboratories to encompass such priority national technical problems. The Joint DoD/DoE Advanced Conventional Munitions (ACM) Program is a non-nuclear weapons technology program consisting of four related development programs. Each has as its basis a Memorandum of Understanding (MOU) between the DoE and the DoD that provides the management and procedural framework for a cooperative program of research and development (R&D) intended to improve/reduce the cost of advanced conventional munitions. The four cooperative programs are: Department of Army (DA) Cooperative Program; DoE/DoD Office of Munitions Program; Low Intensity Conflict Program; and DoD/Defense Advanced Research Projects Agency (DARPA/Department of Army/Marine Corps Armor/Antiarmor (A3) Program.

DARPA sponsored the "Hardison Study" for DoD to assess the utility of electromagnetic and electro-thermal guns for the future tactical weapons systems; to assess the relative merits and risks of candidate weapons; and to identify which key technology should form the basis of a technology development program. The key findings of the study included that technology demonstrators of tank destroyers, local air defense, close fire support, and ATBM weapons could be fabricated by 1992 and have performance superior to current systems if power supplies reach their promise.

Liquid propellant gun technology demonstrations are anticipated in the early 1990s with both electromagnetic and electrothermal gun demonstrations following in the late 1990s.

A summary of total S&T[15] funding for this critical technology is given in the following table.

Funding--Hypervelocity Projectiles ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
460	120	130	130	130	130	130

3. Utilizing the Technology

In addition to weapons applications, railgun technology has lead to new materials manufacturing techniques involving hypervelocity impact deposition for a variety of applications including manufacture of high-speed integrated semiconductor devices.

The electrothermal gun technology has generated substantial new weapons programs, not only in US but also in the FRG and the Israeli Ministy of Defense.

The coilgun technology base has allowed the Navy to begin new programs in electric launchers for aircraft, torpedoes, and sono-buoys.

The components of the projectile technologies and the railgun technologies have been incorporated by SDI into intermediate strategic concepts for terminal defense.

The homopolar machine technology base provides the Navy with solutions for advanced motors and generators for the new all-electric ships. These machines have also found application in new sintering and welding techniques and powering confinement fusion experiments. The DoD programs have also generated new classes of compact multi-gigawatt pulse alternators, which are available to power the new generations of laser, microwave, and particle beam weapons.

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[15] Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

At this point, electromagnetic launcher technology is several years from being incorporated in a fieldable weapon system. Major R&D efforts exist at the basic and applied research level; therefore, there is little domestic manufacturing capability at this time.

2. Projected Manufacturing Capabilities

The military services and DARPA are developing electromagnetic technology for use in strategic and tactical (primarily anti-armor) applications. Many manufacturing and industrial base issues must be resolved before this technology can become viable, including

- Nose tip ablative materials that provide shape-stable nose tips capable of defeating reactive armor systems
- Development and fabrication of high-density, high-strength alloys for penetrator components
- Design and fabrication of high compressive strength, low-density support structure.

Projectile nose tip design is constrained by aerodynamic drag and ablation requirements. Aerodynamic heating causes nose tip heating/recession. Three-dimensional carbon-carbon represents efficient ablator material and exhibits low-shock impedance necessary to defeat advanced armor. Manufacturing capabilities reside in the RV, rocket nozzle, and carbon filament supplier industries.

Penetration is proportional to the cube root of the penetrator density and directly proportional to penetrator length to diameter ratio. Acceleration and balloting induced loads during launch require high compressive and shear strength materials. Efficient load transfer during launch also leads to requirements for rod material properties that vary with the rod diameter. Manufacturing capabilities reside with companies having experience in penetrating munitions, depleted uranium processing, and the associated computational modeling.

Parasitic weight (support structure and sabot) in a hypervelocity projectile (HVP) must be minimized, which leads to requirements for high compressive strength and low-density support structure materials. Fiber reinforced systems (boron/aluminum, boron/magnesium, boron/epoxy silicon carbide/aluminum, etc.) offer the best potential. Load transfer at the structural interface poses the greatest design challenge. Manufacturing capabilities exist in the major aerospace companies and the advanced composite supplier and vendor companies.

E. RELATED R&D IN THE UNITED STATES

Research in electromagnetic gun systems is being carried out in several independent research laboratories and universities in the United States. However, funding support comes chiefly from the government for defense applications.

Overall, the industrial base for electromagnetic launcher technology has been significantly reduced during the past few years due to the reduced funding levels of the government. Research is now primarily focused at the government laboratory level, a few small and large businesses, and several universities. At the government laboratories and businesses, the focus has primarily been on projectile components and gun developments. The other groups conducting research have focused on basic research such as scaling, armature physics, diagnostic development, system configuration trade studies, and experimentation.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Hypervelocity projectile technology encompasses a wide range of techniques and materials required to obtain and maximize the effectiveness of projectiles at velocities greater than 2 km/sec. Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Accurate characterization of projectile flight in atmosphere
- Effective use of advanced propulsion systems
- Application of advanced materials to kinetic energy penetrators
- Three-dimensional characterization of material reaction to warhead efforts.

The table on the following page provides a summary comparison of US and other nations capabilities in selected aspects of this technology. The United States is on a par with the USSR in most of the related technologies.

The Soviets are known to have a considerable interest and probably a research program in the technology of kinetic energy rounds. Soviet work on the use of tungsten alloys for kinetic energy penetrators is well developed and they could have certain advantages over US technology in terms of armor penetration. The Soviets have a strong technological position in the development of high-power sources for electromagnetic or electrothermal guns and in some theoretical aspects of penetration mechanics.

The United States is the leader in all of the critical hypervelocity technologies, but in some areas other countries have comparable capabilities. The United States has the only launcher programs with the long-range goal of velocities about 10 km/sec for space-based application. The United States, thus, is developing a considerable data base in understanding how to achieve such velocities.

Summary Comparison--Hypervelocity Projectiles

Selected Examples	USSR	NATO Allies	Japan	Others
Accurate characterization of projectile flight in atmosphere	▨▨▨	☐☐☐	☐☐	☐☐ Australia, Italy
Effective use of advanced propulsion systems	▨▨▨	☐☐	☐☐	
Application of advanced materials to kinetic penetrators	▨▨		☐☐	
3-D characterization of material reaction to warhead effects	▨▨▨ [a]	☐☐	☐☐	
Overall [b]	▨▨▨	☐☐	☐☐	

[a] Computation deficiencies may be offset by empirical experimentation.
[b] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	☐☐☐☐	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	☐☐☐	capable of making major contributions
▨▨	generally lagging except in some areas	☐☐	capable of making some contributions
▨	lagging in all important aspects	☐	unlikely to have any immediate contribution

SDIO has joint hypervelocity gun programs with Israel, the UK, and the Netherlands. MOUs between these countries provide the basis for mutual access to research. However, since these allies are mainly interested in hypervelocity technology for tactical or theater weapons, any advances in space-based technology occur in the United States only. Discussions with the FRG in the area of advanced chemical hypervelocity guns and Japan in the area of high-temperature switch and inductor technology have taken place.

Because of limited funding and the large capital investment cost required for performing high-energy, repetitive electromagnetic launcher research, the United States and its allies should operate on a mutual dependence basis as much as possible within the security guidelines. Relevant best data, innovative concepts, and manpower assistance should be shared whenever possible to ensure non-duplication of effort.

2. Exchange Agreements

There is a modest level of exchange activity in this area. The NATO Defense Research Group (DRG) program in physics and electronics may provide a mechanism for exchanges of fundamental scientific information in underlying technologies of materials and the physics of weapon target interaction. DARPA has exchanges with certain NATO countries in the area of anti-armor/armor technologies and is in the process of developing an MOU for electrothermal gun and hypervelocity projectiles.

The Technology Cooperation Program (TTCP) provides a vehicle for a range of applicable exchange activities in a number of closely related areas under conventional weapons technology and generic weapons system effectiveness. Again, the level of detail will be limited by classification.

There are only a few related Service exchange programs. These exchanges can, at the technology level, enhance our basic understanding of and ability to model target-weapon interaction and damage effects.

17. HIGH ENERGY DENSITY MATERIALS

A. DESCRIPTION OF TECHNOLOGY

High energy density materials (HEDM) are compositions of high-energy ingredients used as explosives, propellants, or pyrotechnics. They are used in almost all weapons systems, both strategic and tactical, and are fielded by all the Services. They provide the means of getting most ordnance items (whether a bullet, missile/rocket, or kinetic energy vehicle) to target, and once the ordnance item is near the target, they provide the means to kill the target (either by fragments or blast). Thus, HEDM are critial for

- Strategic missile propulsion (strategic offense, deterrence, defense)
- Tactical missile propulsion (air defense, anti-ship strike, deep strike, interdiction, and close air support)
- Kinetic energy vehicle propulsion (space)
- Orbit transfer system propulsion (space)
- On-demand launch system propulsion
- Tactical missile warheads (air defense, anti-ship strike, deep strike, interdiction, and close air support)
- Torpedo warheads (sea combat)
- Bombs (close air support, sea combat, interdiction)
- Mines (mine warfare)
- Components in nuclear devices
- Fuzes.

Seemingly small improvements in HEDM performance can significantly affect weapon system performance. For example

- A 10 percent increase in range for a strategic missile results in several million additional square miles of ocean in which the submarine can conceal itself that the submarine can "hide in" and still launch missiles to hit the target.
- Increased penetration capability of even a few inches can make the difference between penetrating tank armor, or the new hardened concretes, or not penetrating. Penetration most probably results in a kill, while non-penetration would result in a mission failure.
- As enemy weapon ranges increase, air targets will have to be engaged at greater distances. These increased distances, coupled with the decrease in signature of the target will tax the ability of sensors to detect and guide the

missile to the target. The potential for increased miss distances necessitates higher performance warheads that use new HEDM. These increased lethality warheads are critically needed for the advanced air-to-air missile (AAAM) and related outer air battle missiles.

A recently synthesized classified ingredient, CL-20, shows promise that performance gains can be achieved in the near future. For example

- A solid propellant based on CL-20 provides a 17 percent increase in the solid propellant boost propulsion unit, which results in a 50 percent increase in range for air-breathing cruise missiles and allows the platform to launch missiles from a significantly deeper, safer depth.
- Gun propellants based on CL-20 can increase the standoff range of tanks by approximately 1.2 kilometers and increase the projectile velocity by 50 m/s.

The pervasiveness and effect of HEDM on the performance of weapon systems warrants its selection as a critical technology.

Increased performance, while obviously desirable, is not the only major consideration in selecting HEDM as a critical technology. Other major considerations include hazards; signature reduction, primarily in missile propulsion; and availability, dependability, and reliability.

All three Services have programs to reduce hazards without degrading the operational capability of munitions and combat efficiency. As the energy density of the energetic materials has increased (more energy is incorporated into a given volume) the hazards of inadvertent initiation/ignition are also increased. This has serious implications including logistics/readiness (because of quantity-distance considerations, the Air Force and Army in Europe have difficult readiness/storage problems); vulnerability (the Navy has a large insensitive munitions (IM) program to decrease potential hazards of ordnance while maintaining operational capability); and performance/lethality (in many instances, performance and lethality have been sacrificed to decrease hazards). While each Service has its own IM programs, they also have joint efforts and are issuing IM requirements.

All of the Services are involved in trying to reduce signatures produced by their propulsion systems in various areas. For example visible smoke confirms that a missile has been fired and evasive action is required, and it allows one to track back to the launch postion. Visible rocket smoke or muzzle flash also reveals soldiers' positions. In addition, visible smoke and incandescence of the plume from high-performance metallized propellants can be clearly seen by the human eye for many miles, giving a bearing on the missile location, and can be easily detected by satellite, showing that launch occurred and the bearing of the missile. As detectors and sensors have become more sensitive, we have been forced to increase the stealth of our aircraft. However, the stealth of the launch platform can be compromised by the plume signature of the missile launched from the platform. While reduced signature is desirable, it is usually obtained at the expense of performance.

Propulsion units and warheads must be not only available (cost and manufacturing, considerations) but also work reliably after years of handling and storage. For example, the motor must burn stably, within the prescribed thrust-time envelope and with no increase in hazards when fired, regardless of its history.

HEDM must address each of these areas as they relate to one another. To accomplish a mission, trade-offs between performance, hazards, signature, and other factors must be made. For example, to achieve minimal signature propulsion, performance usually suffers. To regain performance, the operating pressure is often increased, which, in turn, often increases the hazards and combustion instability (thereby decreasing reliability). Future requirements have increased demands in each of these areas --demands and trade-offs that can by addressed only through vigorous effort in this critical technology. New ingredients, manufacturing methods, and concepts have recently become available and must be exploited. The HEDM critical technology challenges are shown in the following table.

Critical Technology Challenges for High Energy Density Materials

- Insensitive energetic materials
- High-performance, low-signature, low-hazard, reliable mission propulsion
- High-performance, non-toxic propulsion for space application
- High-performance, low-signature, low-vulnerability gun propulsion
- High-performance explosives for enhanced blast, fragment energy, bubble energy for increased lethality warheads and torpedoes, and shaped charge jets for armor penetration

B. PAYOFF

1. Impact on Future Weapon Systems

Because it has widespread use in various weapon types and functional areas, and because it is a critical enabling technology, HEDM is a critical US technology. The development of future HEDM will enable the United States to utilize

- Minimum-signature, high-performance missile propellants (both for tactical and strategic use) with tailorable fast burn rates
- Warheads with higher lethality to compensate for increased miss distances and allow smaller warheads, more propellant, and longer range missiles
- New generations of underwater explosives to maximize submarine structural damage
- High-performance shaped charges for increased armor penetration
- High-performance launch vehicles and orbit transfer vehicles for space application
- New space-based high-speed kinetic energy kill vehicles
- Advanced low-vulnerability gun propellants giving increased range and damage to target
- Highly insensitive and threat-resistant nuclear weapons
- New pyrotechnically actuated devices with increased speed and performance.

In addition to significant improvements of performance, the HEDM would provide less hazardous, less vulnerable, more reliable, and longer service life munitions.

Some specific goals and payoffs in HEDM, considering CL-20 and other promising HEDM, are given on the following page.

2. Potential Benefits to Industrial Base

While there is a significant industrial base providing HEDM, nearly all of the product is for the DoD, DoE, and NASA. Most non-military applications are NASA and communication satellite launch related. Other non-military applications (such as blasting agents) are not likely to be affected by the type of HEDM produced in this critical technology effort.

Goals and Payoffs--High Energy Density Materials

Application	Goal	Payoff
PROPULSION		
Minimal-signature tactical missile propulsion	• Increase delivered performance over current observable motors • No visible or contrail signature • 1,000% reduction in infrared signature • Radar cross section less than launch platform • No increase in hazards • No combustion instability • Tailorable burn rate	• Increased range (200 nm increase for anti-air, 500 nm for anti-surface), velocity (Mach 2 increase), and payload • Increased element of surprise and greater lethality • Reduced trackability and vulnerability • Reduced obscuration by own missile without increasing hazards nor decreasing reliability
Boost propulsion for submarine-launched cruise missile	• Exceed current booster performance by 50% • Increased launch depth • Low signature plume	• 17% increase in delivered boost performance yields 50% increase in range over existing Tomahawk cruise missile • Current systems compromise launch depth • Decrease ability to detect launch
Solid propulsion for space vehicles	• Retain or exceed performance of current highly toxic propellants • No beryllium or beryllium hydride in propellants • No primary plume signature	• Longer range, more lethal kill • Eliminate toxic beryllium exhaust products • Reduced signature and trackability
Boost propulsion for strategic missiles	• Retain or exceed performance of current high signature metallized propellants • No primary or secondary plume signature	• Increased range, velocity, and payload • Increased amount of ocean to conceal submarine • Decreased risk of launch detection • Decreased risk to launch platform
High-energy gun propulsion	• Increased delivered performance over current gun propellant formualtion • More than 50% increase in mass impetus • Greatly increased burn rates	• Increased range (stand off increase of 2 km) and velocity (200 m/s increase) without increasing hazards or decreasing reliability • Reduced vulnerability
Nonpolluting booster propulsion	• Exceed current performance by 100% • Clean propellant • Stable combustion	• Single stage to orbit • 50% increase in payload • Affordable, on-demand launch system • No launch-site contaminations • Reduced atmospheric pollutants
Orbit transfer vehicle propulsion	• Exceed current performance by 100% • Clean propellant • Stable combustion	• 100% increase in payload • 60% reduction in launch costs • No vehicle contamination

(Continued)

Goals and Payoffs--High Energy Density Materials (Continued)

Application	Goal	Payoff
EXPLOSIVES		
High-energy explosives for shaped charge application	• Increase penetration depth in steel armor plate –50% increase from the current formulations –Meet insensitive munitions requirements	• Increased armor penetration against thick armor increases vulnerable area of enemy tank • Increased safety, enhanced survivability
Bomb fill (blast/frag)	• Exceed performance of current fill • Meet IM requirements and/or 1.6 hazard classification • Affordable, producible materials and processes	• More munitions allowed in ready storage area, increasing number of sorties • Increased safety, survivability • No sacrifice in performance • Low cost
Underwater explosive technology	• 100% increase in shock and bubble energy • Meet IM requirements	• Improved kill of current and future submarine and large surface vessels • Enhanced survivability
Booster technology	• Insensitive/high output booster explosives/devices for initiating insensitive explosives with large critical diameter	• Present reliability low in initiating insensitive HE materials • New devices increase reliability
Follow-through warheads	• Survive hard-target penetration • 50% increase in performance • Meet IM requirements	• In many cases provides difference from current no kill against hardened submarine, land, or ship targets
High-energy insensitive explosives for nuclear weapons application	• 100% increase in performance • Improved vulnerability characteristics	• Higher delivered performance • Greater lethality • Increased safety
Internal blast	• 100% increase in performance • Reactive case • Meet IM requirements	• 50% increase in missile range (smaller warhead) • Kill ship and land targets • Increased missile range due to lighter weather
Explosively formed projectiles	• 50% increase in penetration • Meet IM requirements	• Effective against current and future armor threat • Increased safety, greatly enhanced survivability
Enhanced blast	• 900% increase in blast energy over HE • Meet IM requirements	• 500% increase in effectiveness against shielded targets • Low cost • Increased safety, enhanced survivability
PYROTECHNICS		
	• High output pyrotechnics with fast and tailorable burn rates • Ballotechnics	

C. S&T PROGRAMS

1. Milestones

Milestones--High Energy Density Materials

Technical Area	By 1995	By 2000	By 2005
High-performane, minimal signature missile propulsion for tactical and strategic missiles	• Scale up CL-20 synthesis • Development of minimal signature CL-20 propellant • Performance, hazard, and signature, stability assessment • Synthesize new ingredient (HNHAA or other if more promising) • Technology demonstration of new more insensitive propellants	• CL-20 small motor demo • Motors loaded with CL-20 transition to programs (anti-air-AAAM integral rocket ramjet, anti-surface, and strategic) • Scale-up HNHAA synthesis • Develop, characterize, minimal signature HNHAA propellants • HNHAA plume signature tests • Transfer new propellant to ASRAAM/AMRAAM	• HNHAA small motor demo • Utilize HNHAA-based propulsion for new anti-air and anti-surface missiles, such as AAAM follow-on follow-on programs
High-penetration shaped charges	• High-explosive CL-20 and other new ingredient manufacturing technology • High-energy explosive formulation based on CL-20 • Formulation optimization and scale up • Performance demonstration	• Shaped charge warhead/liner design • Explosive qualification • Sensitivity assessment • HNHAA explosives development	• Anti-armor and hardened concrete penetration weapons for SMAW, Hellfire, AHWS (advanced helicopter weapon system), Dragon follow-on • HNHAA explosive evaluation
Low-vulnerability, high-energy gun propellant	• CL-20 or other new ingredient for high-energy gun propellant formulation • Propellant characterization and optimization • Performance demonstration (i.e., 20 mm cartridge PIP test)	• Formulation scale up • Hazard/sensitivity evaluation • Performance evaluation • Propellant qualification	• Type qualification, weapon evaluation, and production for main battle tank and artillery
Blast warhead	• Subcaliber warhead evaluation • Demonstration of bimetallic case/ explosive concept	• Type qualification • Weapon evaluation for AAM and outer air battle missile	• Warhead production

(Continued)

Milestones--High Energy Density Materials (Continued)

Technical Area	By 1995	By 2000	By 2005
High-shock and bubble energy underwater explosive	• Formulation design • New formulation (ionic oxidizer-metallized compositions) • Small-scale perform-ance testing capability	• Formulation optimization and characterization • Motors loaded with CL-20 propellant for new anti-air and anti-surface weapons	• New weapon design • Utilize HNHAA-based propulsion for new anti-air and anti-surface missiles
Insensitive explosive fill for large munitions (advanced bomb family)	• Explosive candidate selection • Candidate scale up • Production of explosive • Compatible boosting technology • Type qualification	• Advanced bomb production	• Improved advanced bomb
Kinetic energy weapon (high-performance KKV propellant)	• Ingredient selection and formulation design (liquid; ClF_5, OF_2; metal = Be; Solid = CL-20 new burn rate modifiers) • Propellant characteriza-tion and optimization • Propellant scale-up • Performance demonstration	• Propellant scale-up • Processing studies (include environmental impact)	• Incorporate into kinetic kill vehicle
High performance/ launch vehicles and orbit transfer vehicles	• Technical demonstration of insensitive propellants • Scale up of --Li in H_2 --ClF_5O --FN_3/AP --Nitrocubanes	• New insensitive propel-lant in launch system • Small motor demo of new species • Scale up of H atoms in H_2, H in C, K_7O species, HLi_3	• Full-size motors • Small motor demo of new species • Scale up of --di-cations --ArO species --Cyclic N_6 --Cyclic O_8
Non-polluting booster propulsion for space application	• Evaluation of various propulsion concepts (clean, hybrid, or gelled liquid propellant) • Selection of candidate propellant • Propellant characteriza-tion and optimization	• Propellant scale up • Processing and manu-facturing technology • Propellant qualification	• Configuration analysis • Propulsion system eval-uation and production

(Continued)

Milestones--High Energy Density Materials (Concluded)

Technical Area	By 1995	By 2000	By 2005
Ballotechnics technology	• Ingredient selection • Formulation design/ selection • Develop calculation codes • Small-scale testing	• Formulation optimization • Characterization • Energy release mechanism studies	• Performance demonstration • System design • Qualification • Weapon's evaluation and production
High-energy insensitive explosives for nuclear weapon	• Formulation design • Development of new formulation • Performance/sensitivity trade-off studies	• Formulation scale up • Performance evaluation • Hazard/sensitivity evaluation • Explosive qualification	• Weapon evaluation and production

2. Developing the Technology

To meet the goals and milestones described in the preceding table, the DoD, DoE, and industry HEDM programs must encompass scientific programs in areas such as combustion, detonation physics, reaction kinetics, and synthesis of new ingredients. Within each area, care must be taken to balance theoretical and experimental research, to optimize the probability of success and minimize false starts. For example, in the area of synthesis of new ingredients and formulation of propellants and explosives based on these new ingredients, theoretical performance calculations are performed before synthesis of a proposed new ingredient begins. Synthesis efforts begin when a proposed new ingredient promises significantly increased performance. As soon as the ingredient has been made (in very small quantities), fundamental properties are actually measured and performance calculations are made based on these measured values. Those ingredients that do not meet their expected postential are dropped. Similarly, as soon as a sufficient quantity of the ingredient has been synthesized, model propellant and explosive mixes are made and characterized. Only those that show potential continue in the scale-up efforts. Characterization must involve both experimental measurements (such as laser diagnostics) and theoretical predictions (using large, high-speed computers) that were largely unavailable a decade ago. This stringent characterization and screening is mandatory to transfer new HEDM from basic research to advanced development and to minimize time spent on approaches that will not meet the goals.

The technology required to further the HEDM critical technology includes the synthesis of new ingredients; improved materials and hardware; and characterization of performance, hazards, signature, and stability.

In recent years, research in the US has produced promising new HEDM. Successes from these programs can now be exploited to meet technology goals. For example, CL-20 could provide significant advantages for minimal signature propulsion (high performance with minimal signature and reasonable hazards), boost propulsion for the advanced cruise missile (approximately 100 percent increase in system range), increased lethality of warheads (highest detonation velocity and pressure) and increased performance shaped-charge jet armor penetration. Other promising highly energetic solids need to be synthesized. These include super-condensed phase materials, sterically strained molecules, metastable compounds, difluoroamino substituted cyclic or caged compounds, and caged nitramine compounds more energetic than CL-20. For polymeric materials, thermoplastic elastomers offer good performance, improved hazard properties, and reduced costs. Ballotechnics represent a new class of energetic materials that undergo highly exothermic reactions when subjected to an intense shock wave. They could be used for high-output pyrotechnic compositions and also enhance the performance of anti-armor weapons.

The HEDM critical technology will utilize new materials and hardware currently being developed. If increased performance is achieved with higher chamber temperatures, new high temperature resistant nozzles may be required. In addition, these nozzles may employ non-circular cross section design to dramatically suppress infrared signature. New composite case materials and designs may be used to increase performance through higher chamber pressures (if combustion instability can be controlled) and decrease hazards due to bullet and fragment impact. Similarly, new bimetallic warhead cases and reactive warhead cases, coupled with HEDM, may provide significantly increased warhead lethality. In many instances, a kill could be achieved where one is not possible today.

Large-scale tests to screen, characterize, and select new HEDM are costly and could present unacceptable hazard risks. For new HEDM, a critical need exists for new and improved small-scale tests and analysis methods. Following laboratory testing, promising HEDM, such as CL-20, must be scaled up and demonstrated, if timely transition to new munition development programs is to occur.

Many DoD, DoE, and industry programs address each of these areas.

A summary of S&T funding[16] is shown in the following table.

Funding--High Energy Density Materials ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
370	90	100	100	100	100	100

3. Utilizing the Technology

Since most strategic and tactical weapons depend on rocket propulsion to reach their targets, the results of the HEDM critical technology development are needed in many future propulsion systems to increase performance (range, velocity, payload), decrease hazards, and decrease signature while providing increased dependability and reliability. Space applications (getting to orbit, orbit transfer, and kinetic energy vehicles) will also utilize the technology and will not have to rely on propulsion systems that produce highly toxic products.

Similarly, most conventional and strategic warheads utilize high-energy explosives in their design. Explosives based on HEDM are greatly needed to give increased

[16] Funding is derived from programs in the DoD or DoE budgets. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

detonation output (velocity and pressure) and decreased hazard sensitivity. Spin-off applications for short-wavelength lasers, air-breathing propellants, and very energetic fuels are distinct possibilities.

D. RELATED MANUFACTURING CAPABILITIES

1. Existing Manufacturing Capabilities

The primary domestic manufacturing capability for energetic materials is contained within the DoD government-owned contractor-operated (GOCO) munitions production base. Substantial commercially owned energetics manufacturing facilities do exist; however, most of these facilities are highly dependent on government munitions and missile procurements.

2. Projected Manufacturing Capabilities

Implementation of new manufacturing technology for energetic materials, commercially or at GOCOs, involves procurement of selected energetic material from the private sector. Investment in energetics manufacturing capability will be defined by government industrial preparedness/mobilization policy, new energetics material introduced into production, and, finally, by the peacetime budgetary needs for energetic material-based system procurements, as a function of perceived readiness threats posed by the world situation. The DoD has, perhaps, its greatest industrial base investment in the GOCO ammunition production base, which is dominated by energetics manufacturing facilities, either in the propellants and explosives (P&E) and pyrotechnics area or in energetic loading, assembly, and packout (LAP). Addition of robust capabilities for new advanced energetic materials, capability to satisfy newly identified product requirement, such as those for insensitive munitions and redefined environmental process requirements, will add to the need for both peacetime and mobilization-based investment in these facilities.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

Because of the distinct missions of the Army, Navy, and Air Force, their specific needs for energetic materials often differ. However, there is excellent communication of results of basic research through advanced development between these DoD agencies, their DoE counterparts, and with industry. This largely occurs through groups such as the Joint Army-Navy-NASA-Air Force (JANNAF) Interagency Chemical Propulsion Information Group, the Working Party on Explosives, the Joint Logistics Commanders JCTG Groups, and DoD-DoE technical coordinating groups.

NASA, also interested in advances in propulsion for launching of space vehicles, has its own programs but communicates activities and results through the various JANNAF subcommittees.

2. R&D in the Private Sector

There is a significant capability for production of strategic and tactical propulsion units in the private sector (Thiokol, Aerojet, Hercules, etc.). These companies are heavily involved in developing new HEDM through their own (IR&D) efforts and through contracts with DoD agencies.

Production of explosives is done largely within DoD and DoE; very little private production of military type explosives occurs.

Significant basic research and exploratory development is occurring at various US colleges and universities. This work includes synthesis studies and developing new diagnostic techniques.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

The table on the following page provides a summary comparison of the United States and other nations in selected key areas of high energy density materials. Ongoing international research and development indicates potential international capabilities to contribute to meeting the challenges and goals identified:

- Improved properties of insensitive high explosives
- Reduced observable signatures of propellants while maintaining or improving performance
- Improve modeling of energetic material reactions (three-dimensional, combined mechanical/chemical reaction properties)
- Application of energetic materials to ballotechnic processing.

The United States has the lead in the development of certain chemical explosives; however, countries such as France have the ability to match our accomplishments and can incorporate these materials into weapons as quickly, if not more, than will the United States. For example, both France and the UK have now synthesized CL-20, which was first synthesized in the United States in 1987. Primary opportunities for cooperation will occur with France and the UK for advanced HEDM work. Most other countries are not assessed to be actively engaged in the development of new explosives or higher energy density materials beyond the current production state-of-the-art materials such as RDX and HMX.

Summary Comparison--High Energy Density Materials

Selected Examples	USSR	NATO Allies	Japan	Others
Improve properties of insensitive high explosives	▨▨▨▨	□□□□	□□□	
Reduce observable signatures of propellants while maintaining or improving performance	▨▨	□□□	□□□	
Improve modeling of energetic material reactions (3-D, combined mechanical/chemical reaction properties)	▨▨	□□□	□□□□	
Application of energetic materials to ballotechnic processing	▨▨▨▨	□□	□□	
Overall [a]	▨▨▨	□□□	□□□	

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States

- ▨▨▨▨ significant leads in some niches of technology
- ▨▨▨ generally on a par with the United States
- ▨▨ generally lagging except in some areas
- ▨ lagging in all important aspects

Capability of others to contribute to the technology

- □□□□ significantly ahead in some niches of technology
- □□□ capable of making major contributions
- □□ capable of making some contributions
- □ unlikely to have any immediate contribution

Production technology for most common energetic materials, such as nitroglycerine, nitrocellulose, and TNT, is widely available from a number of countries throughout the world. Certain countries, such as Italy and Switzerland, have an acknowledged lead in the production of nitroglycerine. The raw materials for the manufacture of these materials are widely available in every country with an established chemical process industry. At the present time, the French and British appear to have programs to develop new generations of HEDMs that are similar to chemicals currently under development and certification in the United States. These materials are approximately 20 percent more energetic than RDX and appear to have acceptable shock sensitivity and related parameters. There have not been any noticeable development efforts in other countries (allied or friendly) that would indicate a comparable program at this time; however, this assessment is based more on a lack of confirming data than specific data.

Development of energetic materials for both liquid- and solid-fueled missiles and rockets is widespread throughout the world. The French are now publishing their own textbook for the design and formulation of fuels for missiles, a clear indication of their progress in the missile age. Japan, Israel, France, the UK, Australia, Sweden, Norway, Canada, the FRG, Italy, Switzerland, South Korea, Taiwan, Indonesia, India, and Pakistan all have programs for the development of solid-fueled and/or liquid-fueled engines for missiles and rockets. The relative accomplishments of these countries varies from state of the art to primitive. However, at this time the rate of advance is very rapid, and each of these countries has access to all of the necessary infrastructure and technological support to develop state-of-the-art HEDM, comparable to many currently under R&D programs in the United States.

The Soviet Union has an extremely large R&D program for the development of HEDM, which in some respects is more advanced than that in the West. In fact, the Soviets have made investments in several areas for which comparable programs do not exist in the West.

2. Exchange Agreements

Energetic materials have long been the subjects of international agreements. The Technology Cooperation Program (TTCP) also provides exchange mechanisms through a number of activities in conventional weapons.

All of the Services have a number of data and information exchanges with NATO allies as well as with a few other nations. Topics range from basic physics of materials and detonation to application of materials as explosives, propellants (both guns and rocket motors), reactive armor, and pyrotechnics and logic devices in safing, arming, and fuzing devices. There are also exchanges on safety and disposal. In addition, the United States has agreements with a number of non-NATO allies in both basic materials and selected applications.

The area of high energy density fuels for air-breathing propulsion is also integral to and is an aspect of exchange under agreements relating to air-breathing propulsion.

18. COMPOSITE MATERIALS

A. DESCRIPTION OF TECHNOLOGY

The creation of new structural materials is revolutionizing the development of vehicles, buildings, and structures around the world. Composite materials technology promises significant improvement for weapons performance, design, and affordability. Furthermore, composite materials have broad dual-use applications in industry and the military. These factors combine to warrant the selection of composite materials as a critical technology.

Composite materials are defined as a combination of two or more constituents that are combined together in such a manner that the resulting substance has selected properties superior to those of the individual components. Composites generally consist of fibrous or particulate reinforcements held together by a common matrix material. Composites are classified according to their matrix. Polymer matrix composites (PMCs), metal matrix composites (MMCs), ceramic matrix composites (CMCs), and carbon/carbon (C/C) composites and their hybrids are the major classes of composite materials under development in the DoD. Continuous fiber reinforcements enhance preferred direction structural properties of a composite.

Composite materials are becoming increasingly important to the design and manufacture of present and future military systems. In some cases, such as the National Aero Space Plane (NASP), advanced gas turbines, deep submergence vehicles, and spacecraft, composites are recognized as the enabling technology required for fulfillment of demanding thermal, structural, and mechanical requirements.

High-strength/light-weight composite materials are essential to many other critical military applications. This technology area involves product and manufacturing process technologies such as structural analysis (e.g., fatigue and life cycle factors), rapid solidification techniques, plasma flame spraying, advanced fiber technology, and fiber-matrix interface technologies. Coatings technology, particularly that used for corrosion and oxidation resistance of composites, are also of great importance to military applications. Some coatings are used as a barrier against fiber/matrix chemical interactions that can degrade the strength of a composite material.

Critical Technology Challenges in Composite Materials Technology

- Ultra-high temperature metal, carbon, and ceramic matrix composites
- Exterior and reinforcement coatings
- Aerothermal response and life cycle effects

B. PAYOFF

1. Impact on Future Weapon Systems

Composite materials technology affects virtually every new weapon system. These materials are required in a wide spectrum of vehicle structures, including high-temperature propulsion systems, hypervelocity vehicles, short take-off and landing (STOL) and vertical take-off and landing (VTOL) vehicles, as well as for spacecraft, protection against directed energy threats, and advanced hull forms and submarine structures. Next-generation composite materials and structures will emphasize additional multi-function capabilities (which integrate sensors and countermeasures), resulting in options for military systems that are unheard of today. Advanced composite materials will fulfill the needs of the following series of weapon systems type requirements:

- Damage-tolerant composite materials and hardening concepts for protection of platforms and weapons systems against operational hazards and advanced threats
- High thermal conductivity materials for critical thermal management applications such as heat dissipation from electronic devices, infrared signature suppression, and weight-efficient radiators
- Thermostructural composite materials for improved efficiency and reliability of advanced propulsion systems (gas turbines, air-breathing missile motors, rocket nozzles)
- Submarine system composite materials for improved capabilities in depth, speed, and covertness and for cost reduction
- Erosion/ablation resistant composite materials for all-weather capability and improved performance of missiles
- Electromagnetic absorbent hybrid composite materials having sufficient strength and stiffness to serve as useful structural members for aircraft, ships, and missiles (non-parasitic).

Advanced composite materials technology offers opportunities for substantial improvements in performance, reliability, and reductions in cost. The ongoing demonstration of a PMC armored-vehicle turret and hull will help lead to the broader adoption of these components to a family of ground vehicles, where weight savings of 25 to 50 percent can be achieved with accompanying cost savings. High-temperature composite materials are one of the enabling technologies to increase engine thrust by more than 50 percent and reduce fuel consumption by as much as 40 percent. The use of new high thermal conductivity composites in electronic device components can reduce the thermal resistance between chip and heat sink by 15°C, affording a 50 percent increase in reliability.

2. Potential Benefits to Industrial Base

The current value of components produced from advanced composites in the United States is less than $2 billion per year. However, by the year 2000, US production is expected to grow to nearly $20 billion. This estimate includes only the value of the materials and structures; it does not include the value of the finished products, whose performance, and therefore competitive posture, is improved by use of the materials. When the overall value of these products is taken into account, use of advanced structural composite materials is likely to have a dramatic effect on gross national product, balance of trade, and employment.

Military demand for high-performance materials in the United States has already created a thriving community of advanced materials suppliers. These suppliers are also seeking commercial applications for their materials. At present, though, advanced materials developed for military applications are expensive, and fabrication processes are poorly suited for mass production.

Potential US commercial end users believe that major use of these materials will not be profitable within the next five years, the typical planning horizon of most firms. In many cases, 10 to 20 years will be required to solve remaining technical problems and to develop rapid, low-cost manufacturing methods. Investment risks are especially high for commercial end users because the costs of scaling up laboratory processes for production are enormous, and the rapid evolution of technology could make these processes obsolete. Hence, there is little commercial incentive for advanced materials technologies in the United States.

The potential for advanced materials in the manufacturing sector will not be realized unless companies perceive that their criteria for investment in R&D and production will be met. The investment criteria used by advanced materials companies vary depending on whether they are materials suppliers or users; whether the intended markets are military or commercial; and whether the end use emphasizes high materials performance or low cost.

Suppliers of advanced structural materials tend to be technology driven; they are focused primarily on the superior technical performance of advanced materials and are looking for both military and commercial applications. Suppliers tend to take a long-term view, basing investment decisions on qualitative assessments of the technical potential of advanced materials. On the other hand, users of advanced materials tend to be market driven; they are focused primarily on short-term market requirements, such as return on investment and time to market.

Frequently, advanced materials suppliers and users operate in both military and commercial markets. However, the investment criteria employed in the two markets are very different. Defense contractors are able to take a longer term perspective because they are able to charge much of their capital equipment to the government and because the defense market for the materials and structures is well defined. Commercial end users, on the other hand, must bear the full costs of their production investments and face uncertain market terms. Their outlook is therefore necessarily shorter term. This difference in market perspective has hampered the transfer of technology from advanced materials suppliers (who frequently depend on defense contracts to stay in business) to commercial users, and it underlines the importance of well-defined markets as a motivating force for industry investments in advanced materials.

C. S&T PROGRAMS

1. Milestones

Milestones--Composite Materials

By 1995	By 2000	By 2005
• Development of high-temperature metal and ceramic composite engine components • Pervasive application of composite materials in aerospace vehicles and advanced ship hulls	• Qualification of composite materials for thermal management and weight reduction in electronic devices • 25 to 50% weight reduction in airframes • Significant reduction in radar and infrared signatures • 20 to 40% reduction in fuel consumption in gas turbines	• Widespread use of advanced composite materials in most US weapons systems and platforms

2. Developing the Technology

Major DoD thrusts in the composites area--with large payoffs for the future--include lighter weight, stiffer structural composite materials (spacecraft); higher temperature, high-performance applications (gas turbines); and hybrid composite materials with multi-functional capability (low observables, survivability). Pertinent research programs addressing these requirements encompass PMC, MMC, CMC, and C/C composite systems. The programs are aimed at developing fundamental knowledge of the processing, structural property relationships, failure mechanisms, characterization, and life prediction and non-destructive evaluation of these materials.

Examples of programs being directed at specific requirements follow:

- Reinforced titanium and aluminides for advanced gas turbine engines and NASP structural components
- Development of copper micro-composites and graphite-reinforced copper as candidates for NASP heat exchangers
- Development of oxidation resistant c/c and CMC for propulsion systems
- Use of low dielectric fibers in ceramic composites for antenna window applications
- Development of aluminum, magnesium, and thermoplastic matrix composites (utilizing ultra-high modulus carbon fibers) for space structures.

3. Utilizing the Technology

DoD's effort in high-performance structural materials technology continues to affect virtually all major weapons systems (fixed-and rotary wing-aircraft, spacecraft, missiles, and ground and sea-going vehicles).

Polymer matrix composites are the most mature composite technology. Beginning in the 1970s, composites were used in military applications (such as fighter aircraft and rocket motor casings), and they now have a solid record of exceptional performance and reliability. Composites rapidly are becoming the baseline structural material of the defense aerospace industry. This sector has been estimated to consume as much as 80 percent of all high-performance PMCs. Growth projections for aerospace usage of composites have ranged from 8.5 percent per year to 22 percent per year. The primary matrix materials in aerospace applications are epoxies, and the most common reinforcements are carbon/graphite, aramid (e.g., Kelvar 49), and high-strength glass fibers. However, high-temperature thermoplastics (such as PEEK) are considered by many to be the matrices of choice for future aerospace applications. Composites are used extensively today in small military aircraft, military and commercial rotorcraft, and prototype business aircraft. The next major aircraft market opportunity for composites is in large military and commercial transport aircraft.

The principal advantages of PMCs in aerospace applications are their superior specific strength and stiffness compared with metals, resulting in weight savings of 10 to 60 percent over metal designs; a 20 to 30 percent weight saving is typical. This weight reduction can be used to increase range, payload, maneuverability, and speed or reduce fuel consumption. A pound of weight saved on a commercial transport aircraft is estimated to be worth \$100 to \$300 over its service life, depending on the price of fuel, among other factors. This high premium for saved weight is unique to the aerospace industry, which is why aerospace applications of PMCs lead all other applications in growth rate. Additional advantages of PMCs are their superior fatigue and corrosion resistance and vibration damping properties.

Advanced composites have become essential to the superior performance of a large number of fighter and attack aircraft. Indications are that composites may account for up to 40 percent of the structural weight of the Advanced Technology Fighter (ATF), which is still in the design phase. Because the performance advantages of composites in military aircraft more than compensate for their high cost, the military market is likely to be the fastest growing market for advanced composites during the next decade. One estimate, which considers existing production and the ATF, projects a growth from about 0.3 million pounds per year in 1985 to 2 million pounds per year in 1995.

If glass fiber reinforced composites are included, the volume of composites used in commercial and business aircraft is about twice that used in military aircraft. In current commercial transport aircraft, composites make up about 3 percent of the structural weight and are used exclusively in the secondary (not flight-critical) structure. However, several companies utilize composites in the wings, empennage, and fuselage of business aircraft.

By the year 2000, composites could make up 65 percent of structural weight of commercial transport aircraft. Estimating a structural weight of 75,000 pounds per aircraft and production of 500 aircraft per year, this application alone should account for 24 million pounds of advanced composite per year. Assuming a starting material value of \$60/lb, the market in the year 2000 is estimated to be approximately $1.5 billion for the composite material alone. A more conservative estimate, which assumes that no new commercial aircraft will be built by 1995, has placed the US composite commercial airframe production at between 1 and 2 million pounds during that year.

With the exception of the all-composite business aircraft prototypes, which are in the certification process, composites have been used more extensively in helicopters than in aircraft. Military applications have led the way, and the advantages of composites are much the same as in aircraft: weight reduction, parts consolidation, and fatigue and corrosion resistance. During the past 15 years, composites have become the baseline materials for rotors, blades, and tail assemblies. Future military helicopters, such as the Army's LHX or the Navy's tilt-rotor V-22 Osprey, have specifications that force designers to consider composites, which are likely to comprise up to 80 percent of the structural weight. Materials such as graphite/epoxy are likely to be used in the airframe, bulkheads, tail booms, and vertical fins, while the less stiff glass/epoxy composites will be used in the rotor systems. As with aircraft, there could be a long-term trend away from epoxy resins and toward thermoplastic resins.

Composites of all types, including ceramic, polymer, and metal matrix composites, are ideal materials for use in space-based military systems, such as those associated with the Strategic Defense Initiative (SDI). Properties such as low density, high specific stiffness, low coefficient of thermal expansion, and high-temperature resistance are all necessary for structures that must maneuver rapidly in space, maintain high dimensional stability, and withstand hostile attack.

A summary of total S&T funding[17] for this critical category is given in the table below.

Funding--Composite Materials ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
670	170	180	180	180	180	170

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

During the past decade the composites industry has emphasized the importance of new and improved composites manufacturing capability as a critical need for expanded application of composites materials. As a result, many cost-reducing manufacturing techniques have been introduced, through automation of the lay-up, handling, and cure of composite materials. Most significant has been the development of tape lay-down machines, which nearly eliminate the hands-on labor for this operation and increase

[17] Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

material lay-down rates up to 10 times that of hand lay-up. Laminate part quality improvement with less rejects has also been noted. Other automated techniques developed and being used include a complete ply laminator and robotic lay-up of plies. Several major aerospace companies have established (or have under development) complete composite fabrication centers that include a high degree of automation, ranging from incoming materials inspection to lay-up, cure, and assembly. Other contemporary DoD manufacturing technology investments supporting and utilizing this critical technology include adhesively bonding composite materials, producing thermoplastic secondary aircraft structures, reducing cost of fuselage composite components and structures, and improving techniques for nondestructive testing of composite materials.

2. Projected Manufacturing Capabilities

Even with the most advanced manufacturing techniques and equipment, composites typically are being used only when system performance gains (i.e., fighter aircraft and stealth characteristics) justify the additional cost. It is therefore expected that a renewed emphasis will be placed on new manufacturing processes that can provide a very substantial reduction in end item cost. Programs on automated techniques that can significantly increase the pounds per hour of material lay-down, and processes that can avoid lengthy autoclave cures and reduce assembly costs and quality control costs are anticipated.

Each of the military departments has aggressively pursued manufacturing developments of PMC to improve quality and reduce cost. These new developments have been made available to the entire aerospace industry. Also, renewed composite application interest by NASA for commercial aircraft (High-Speed Civil Transport (HSCT)) has resulted in some new design and manufacturing development programs.

The basic material industries (fiber and resin) are vital to maintaining and increasing the composites industry and have responded quite well to national interests in maintaining a lead position in composites manufacturing.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

Composite materials research and development is underway at NASA, DoE, Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Oak Ridge National Laboratory (ORNL), and the Sandia Corporation. In addition, composite materials work is also underway at the Department of Commerce (DoC)/National Institute for Science Technology (NIST) and to a lesser degree under the sponsorship of the National Science Foundation (NSF). The NASA high-temperature composite materials work is tightly coordinated with the DoD NASP and Integrated High Performance Turbine Engine Technology (IHPTET) programs through coordinating groups. The NASA composite materials work related to advanced civil transports is also coordinated with DoD through conference coordinating groups such as the DoD/NASA/Federal Aviation Administration (FAA) Conference on Fibrous Composites in Structural Design.

Overall, most of the R&D on high-temperature composite materials is underway in the NASA and DoE laboratories, whereas the lower temperature PMC R&D is being conducted at the DoC/NIST and NSF, as well as at NASA and DoE.

2. R&D in the Private Sector

Research and development is proceeding in all aspects of composite materials in government laboratories, industry, and universities. Research areas that are most appropriate are low-cost manufacturing processes and optimization of structures.

Extensive use of PMCs by the automotive industry would bring about completely new industries, including a comprehensive network of PMC repair facilities, molding and adhesive bonding equipment suppliers, and a recycling industry based on new technologies. Current steel vehicle recycling techniques will not be applicable to PMCs, and cost-effective recycling technologies for PMCs have yet to be developed. Without the development of new recycling methods, incineration could become the main disposal process for PMC structures. The lack of acceptable recycling and disposal technologies could translate into higher cost for PMC structures relative to metals.

Numerous universities have established composite centers; a Center of Excellence on Manufacturing Science of Composites has been established at the University of Delaware. Research being supported is aimed at combining manufacturing science and engineering design with an emphasis on building quality into thick section composites typically used in military applications. Materials forms being investigated include both thick section laminates and textile woven forms using thermosetting and thermoplastic matrix materials. Particular emphasis is being given to cure sensing and in-process control fabrication of thick section composites, thermal and mechanical characterization, structure-property relationships, and methods for nondestructive testing.

Additional research in the university community includes DoD-funded investigations of micro-mechanics processes, continuum to the atomic scale, tailoring of mechanical behavior through appropriate chemistries at the composite interface, process mechanics (in metal matrix composites), and fracture mechanics.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

The following table below provides a summary comparison of the United States and other nations in selected key areas of materials. Ongoing international research and development indicates potential international capabilities to contribute to meeting the US challenges and goals including

- Development of composite materials capable of retaining structural properties at high temperatures
- Application of structural composites to reduce observables
- Development of improved nondestructive evaluation techniques for advanced composites

- Improved characterization of composite material response to weapon effects
- Improved modeling and prediction of life cycle failure.

Summary Comparison--Composite Materials

Selected Examples	USSR	NATO Allies	Japan	Others
Development of composites materials capable of retaining structural properties at high temperatures				
Application of structural composites to reduce observables				Israel
Development of improved NDE techniques for advanced composites				
Improved characterization of composite material response to weapon effects				
Improved modeling and prediction of life cycle failure				
Overall [a]				Israel

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
	significant leads in some niches of technology		significantly ahead in some niches of technology
	generally on a par with the United States		capable of making major contributions
	generally lagging except in some areas		capable of making some contributions
	lagging in all important aspects		unlikely to have any immediate contribution

Both Japan and NATO have active materials development programs and may lead in selected aspects of materials research. The United States has an overall lead, however, in the design and effective use of advanced materials in specific military applications. Primary opportunities for cooperation will occur with Japan in the area of ceramics and with NATO countries in the area of ceramic composites for jet engine hot sections and, perhaps, in selected processing technologies. These countries are also actively pursuing the application of advanced materials to robots for industrial and other uses (e.g., space robots).

The allies typically follow the US lead in the application of advanced materials to military systems, but the use of composites is now well established in every country with a significant arms industry, and other nations may lead in commercial applications. The industrially advanced West European countries and Japan have established themselves as important suppliers to the United States. Japan is embarking on a major initiative in materials to support development of next-generation air transports. Their stated intent is to establish a center for research and development of new materials for use at temperatures as high as 2000°C.

The French are among the world's leaders in production of ceramic composites and have embarked on a joint venture with a major US company. As in the United States, there is considerable interest in attaining higher turbine inlet temperatures to increase engine performance utilizing those materials. In addition to France, the UK, the FRG, and Japan are active in the field. An active research program in materials research is also underway at the Swiss Ecole Polytechnique Federale de Lausanne. The materials science department there draws scientists from France, the FRG, the UK, and Italy in about equal numbers. The international nature of research appears typical of much of the present materials research within NATO. These programs could be strengthened further with European unification in 1992. In materials and structures R&D, the Soviet Union is second to only the United States and Japan.

Because of the need for improved military capability, composite materials are being designed into a variety of US military equipment. More widespread utilization of these materials is expected to occur in the near term. Composite materials are beginning to appear in foreign military equipment. The United States is judged to have the world leadership in composite materials. This lead is being rapidly eroded, however, by a combination of industrial technology transfer, such as is now occurring in aircraft composite technology, and strong R&D efforts by many other nations.

Many of the newly industrialized countries, particularly in the Pacific rim, are expected to direct a significant portion of their R&D and manufacturing resources to weapon systems due to the high profits to be realized from military sales. These countries are expected to establish a strong infrastructure to produce composite materials in support of this industry.

Advanced structural materials industries have become much more international in the past several years. In collaboration with industry, governments around the world are investing large sums in multi-year programs to facilitate commercial development. Through acquisitions, joint ventures, and licensing agreements, the firms involved have become increasingly multi-national and are able to obtain access to growing markets and achieve lower production costs. Critical technological advances continue to be made outside the United States, for example, carbon fiber technology developed in the UK and Japan and hot isostatic pressing technology developed in Sweden.

This trend toward internalization of advanced structural materials technologies has many important consequences for government and industry policy makers in the United States. They can no longer assume that the United States will dominate the technologies and the resultant applications. According to a National Research Council Report, the United States is already lagging behind other nations in applying advanced materials to manufacturing processes.

The technology flow into the United States may soon be just as significant as that flowing out. Moreover, the increasingly multi-national character of material industries suggests that the rate of technology flow among firms and countries is likely to increase. The United States will not be able to rely on a superior R&D capability to provide an advantage in developing commercial products. Furthermore, if there is no existing infrastructure in the United States for quickly appropriating the R&D results for economic development, the results will quickly be used elsewhere.

2. Exchange Agreements

There is a high level of exchange activity in the area of high-strength composites, in both basic materials and a wide range of applications. NATO programs for physics and electronics provide a mechanism for exchange of scientific information regarding the basic physics of structural material. Defense Advanced Research Projects Agency (DARPA) memorandums of understanding (MOUs) specifically cover the use of composites in armor and anti-armor.

The Technology Cooperation Program (TTCP) provides a vehicle for a range of applicable exchange activities relating to basic material, ceramics, and materials performance.

Each of the Services also has exchanges, primarily with NATO and with friendly nations in areas of specific interest. These include exchanges of technology in such diverse areas as structures and materials for combat aircraft and basic studies in fatigue properties of aircraft structures and dynamic behavior of materials under stress.

19. SUPERCONDUCTIVITY

A. DESCRIPTION OF TECHNOLOGY

Conventional electrical, electronic, and electromagnetic devices and systems (e.g., power lines, computers, and electric motors and generators) suffer performance limitations and undesirable power losses as a consequence of the electrical resistance inherent in normally conductive materials. Researchers have long sought ways to overcome these limitations. A remarkable advance was achieved in 1911 with the discovery of superconductivity (the resistance-free flow of electric current) at temperatures a few degrees above absolute zero. From 1911 to 1986, remarkable progress was achieved with the development of revolutionary superconducting magnets, motors, generators, sensors, and ultra-efficient, ultra-fast analog and digital electronic devices and systems. In many applications the much higher performance achieved through use of superconductivity more than compensated for the inconvenience of providing for refrigeration near absolute zero. In 1986, a new class of higher temperature superconductors was discovered, which has greatly reduced refrigeration requirements for the existence of superconductivity. This advance has greatly expanded practical realms for the application of superconductivity, many of which offer exceptionally high potential for military systems of unprecedented performance.

Thus, superconductivity technology of current interest encompasses both traditional metallic low-temperature superconductors (LTS) (transition temperature less than 23K) and the new oxide high-temperature superconductors (HTS) (transition temperature as high as 125K or more). The most commonly used LTS material is a very ductile alloy of niobium and titanium, which is corrosion resistant, is easily formed into supermagnets, and exhibits moderately high superconducting performance. Brittle metallic LTS materials (e.g., Nb_3 Sn) also offer higher performance (higher current density at higher magnetic fields at higher temperatures) but are difficult to fabricate because of their brittleness. The LTS materials niobium and niobium nitride are commonly used in superconducting sensor and electronics applications. With these materials, large arrays of Josephson junctions are readily fabricated.

HTS materials offer much higher operating temperatures and much higher operating magnetic fields, and they appear to possess potential for supporting electric current densities adequate for many applications. However, most HTS materials possess highly anistropic properties, are very brittle, and are highly susceptible to corrosion. HTS end products, whether supermagnets or electronic devices and systems, are more difficult to fabricate.

DoD superconductivity R&D extends from searches for theoretical understanding, to materials characterization, materials processing, invention and architecture, and finally engineering test models and operational systems that involve superconductivity. Of concern are issues related to the basic properties of superconductors, their manufacture and fabrication into usable configurations, and their unique device and systems applications that capitalize on their abilities to support loss-less DC currents and low-loss ac currents, levitate, shield magnetic and electromagnetic fields, sense magnetic and electromagnetic fields with unmatched sensitivity, transmit electronic signals with extremely little distortion, and fulfill analog and digital electronics functions at speeds 10 to 20 times faster and at power dissipation 1,000 times less than is currently possible with semiconductors. Critical to all such applications are efficient and reliable refrigeration systems.

Critical Technology Challenges in Superconductivity

- HTS materials and processing
- LTS applications
- Integration with semiconductor devices

Large-scale LTS technology has progressed to the point where thousands of supermagnets are now in routine use around the world in magnetic resonance imagers and in high-energy particle accelerators. The first steps have also been taken for the application of LTS to military systems such as compact and efficient electric drive systems for ships. LTS sensors and analog electronics devices have also been highly developed. However, LTS digital electronic systems are at an earlier stage of development, and the United States trails Japan in this high-risk, high-potential-payoff technology. Overall, LTS technology promises high utility not only in its own right, but also in modeling systems to be later executed in HTS materials when feasible.

HTS materials development is in its infancy. Because HTS materials are difficult to process, a heavy and sustained investment in R&D will be required if their apparent potential is to be realized. Production of high-quality films and development of patterning techniques are high-priority goals, as are high-current-density bulk HTS materials suitable for power transmission, supermagnets, motors, and generators. The course of HTS development will probably proceed from low-power, low-magnetic-field passive analog electronic components, to electromagnetic sensors, digital electronics, small supermagnets, and finally large-scale supermagnet applications.

B. PAYOFF

1. Impact on Future Weapon Systems

Potential superconductivity applications, many of which have already been tested in LTS prototype form, include more compact, higher efficiency electric drive systems for ships (and possibly land vehicles and aircraft), electric generators, electric energy storage systems for directed energy weapons, superconducting cavity particle accelerator directed-energy weapons, electromagnetic guns and aircraft catapults, magnetic and electromagnetic shields, supermagnets and cavity resonators for microwave and millimeter-wave generation. Further applications involve magnetic and electromagnetic sensors (DC through infrared), infrared focal plane arrays, superconducting quantum interference devices (SQUID), magnetic gradiometers and magnetometers, high-power sonar sources, ultra-high-speed, ultra-compact signal processors and computers, high-performance low-noise communications and surveillance systems, superconducting antennas, and superconducting gyroscopes, inertial sensors, gravimeters and magnetic mine detectors. Many of these systems are unique, having no normal conductor counterparts, e.g., superconducting magnetic energy storage systems and SQUID sensors. The development of such SQUID sensors will provide new magnetic anomaly detection (MAD) methods for finding acoustically quiet submarines. In other instances new capabilities can be brought to platforms incapable of supporting conventional semiconductor counterparts because of size, weight, or power requirements. For example, with superconducting electronics technology, placing ultra-high-speed supercomputer capabilities on board aircraft and spacecraft should be feasible; this capability currently is not feasible with semiconductor technology because of its large input power requirements (200 kilowatts) and associated massive cooling system requirements. Further, the development of efficient superconducting electric motors for ship drive will permit the use of advanced hull forms with exceptional operational and warfighting capabilities.

In all cases, the performance advantages of such systems must be adequate to more than compensate for the necessary refrigeration requirements.

2. Potential Benefits to Industrial Base

DoD efforts in superconductivity offer substantial potential for beneficial effect on the industrial base. The development of compact, efficient motors and generators as well as low-loss cables for power transmission and energy storage devices will lead to improved distribution and utilization of electrical energy. Such future systems will offer greater immunity from brown-out, be more easily repairable (due to small size), and, where necessary, allow local control of available energy to improve industrial production. Magnetic resonance imaging, a billion-dollar-per-year industry, will become more accessible for routine use, thereby minimizing invasive diagnostic surgery. Progress in superconducting electronics is expected ultimately to lead to higher performance supercomputers and mainframe computers. Advanced, very stable oscillators will permit increases in communications spectral density. Magnetic sensors based on SQUID technology will be used for medical monitoring and diagnosis of brain function.

C. S&T PROGRAMS

1. Milestones

Milestones--Superconductivity

Technical Area	By 1995	By 2000	By 2005
Materials and processing	• Higher transition temperature HTS materials • Quality HTS tunnel junction arrays • Large-area HTS films for shielding and cavity resonators • Theoretical understanding of HTS	• Higher transition temperature HTS materials • Quality HTS tunnel junctions in large arrays • HTS conductors suitable for supermagnets	• Codified manufacturing processes for materials production and fabrication
Sensors	• LTS IR focal plane arrays • HTS sensors, DC to IR • LTS inertial and gyro sensors	• LTS MAD ASW systems • HTS IR focal plane arrays • HTS inertial and gyro sensors	• Widespread use in a variety of sensor platforms
Superconducting electronics	• LTS analog communications and surveillance systems • HTS analog communications and surveillance components • HTS A/D converters • LTS Nb/NbN digital chip-level technology • HTS interconnects for semiconductor circuits • HTS digital electronics array technology	• HTS analog communications and surveillance systems • LTS Nb/NbN digital signal processor and memory • HTS digital chip-level technology • HTS satellite system	• Widespread use of superconducting electronics
Supermagnet-based applications	• Prototype LTS-rotating electrical machines • Prototype LTS magnetic energy storage system • Prototype LTS magnetic gun • Test of LTS MHD ship propulsion system • Modest-performance HTS supermagnets	• Engineering of operational LTS rotating electrical machines • Engineering of operational LTS magnetic energy storage system • Engineering of operational magnetic gun • Engineering of operational MHD ship propulsion system • High-performance HTS supermagnets	• Widespread use of superconducting magnets in industry, academia, and defense
Particle accelerators	• Low-loss HTS cavity resonators	• Prototype HTS cavity resonator particle accelerator	• Widespread use in academia and defense research

2. Developing the Technology

a. Materials Research and Development

Understanding the properties and the physics of the newly discovered HTS materials is of utmost importance. Such understanding is needed to guide the search for new materials and to determine the limitations of the existing materials. Further, the search for new materials will include not only the ceramic class but organics as well. LTS metallic materials will also be included. A new ductile LTS material with a superconducting transition temperature, T_c, over 30K and capable of supporting high critical current densities, $J_c(H)$, at high magnetic fields, H, would find immediate use in power applications.

Although recent progress has been made, one of the biggest problems with bulk, polycrystalline HTS materials remains the modest value of $J_c(H)$. Better understanding of magnetic vortex pinning mechanisms is required if further progress is to be made in this arena.

Other critical issues are concerned with material synthesis and processing. The new HTS materials are made in bulk forms only by high-temperature processing. This makes reactions with container materials difficult to control, and the desired purity of the new HTS materials is difficult to achieve. Further, polycrystalline materials must be prepared with very clean grain boundaries to permit understanding of the effects of such boundaries on critical currents.

Fabrication issues also arise from the fact that the oxygen content is very temperature dependent and hence is difficult to control, and reproducible samples of good quality are not easily obtained. A variety of fabrication techniques must still to be explored. Fabrication difficulties must be overcome if a successful technology is to be established for these new HTS materials.

Thin-film superconductor processing is being explored, because it forms the basis of integrated circuitry for electronic applications and offers the potential for composite conductors with superior engineering qualities. A variety of promising film methods are being examined, but no clearly superior method has been found. Single crystal growth (for both bulk and film specimens) is important to improved understanding of the basic physics and applications potential of these materials.

Noise sources in thin films, such as thermally induced magnetic flux motion, are being examined and minimized for sensitive detectors of electromagnetic radiation. These noise sources must be investigated in both the HTS and the LTS materials, as both will be used in electronics applications.

Studies of radiation effects in HTS materials have been initiated. For military applications, these effects will be important and must be fully understood. Similarly, stress/strain effects are important topics of study, as they will affect system performance and reliability for both electronic and power applications of superconductivity.

b. Electronics Research and Development

The very low electrical loss and the unique quantum physics properties of the superconductive tunnel device can be incorporated into a wide variety of applications of interest in surveillance and communications systems. The advent of high-temperature materials and their reduced refrigeration requirements will expedite the introduction of high-frequency, high-speed devices and components into systems.

Low-Insertion-Loss, High Q-Value Components: The high-frequency surface losses of superconductors are much lower than those of normal metals at the same operating temperature. This permits development of passive components, such as filters, resonators, and couplers, with greatly reduced transmission losses of input signals from the antenna to the receiver. This reduction in losses could lessen the complexity of many systems by rendering amplifiers unnecessary in long transmission lines and by reducing the required transmitter power. The higher Q-values will result in enhanced frequency selection and the ability to reject spurious out-of-band signals. All of these advantages will result in high-frequency systems that are higher in performance, less complex, smaller in weight and volume, and lower in cost.

Super-Directive Antennas: The very-low electrical losses of a superconductor can be used to build very-small (that is, with lengths small compared to the wavelength of the radiation of interest) antennas with performance comparable to that achieved with large conventional antennas. These very small antennas can be configured into arrays with dimensions smaller than a half wavelength, which can have very directional radiation patterns. Neither of these antenna concepts can be realized using normal metals technology. These antennas will have their greatest effect on platforms with severe area constraints, such as satellite and aircraft applications and homing systems on missiles.

Low-Noise, High-Frequency Amplifiers, Mixers, and Detectors: The superconductor-insulator-superconductor device has been used to build high-frequency mixers, detectors, and amplifiers with noise characteristics close to those predicted for quantum-limited operation. In this extreme, one electron is introduced into the external circuits for each high frequency photon incident on the devices. This performance has been demonstrated for frequencies up to about 100 GHz. If these devices can be optimally embedded in suitable circuits, quantum-limited operation to even higher frequencies will be realized. These very-low-noise amplifiers can be used in many DoD systems such as electronic intelligence, satellite communications (low receiver noise can result in greater range or reduced transmitter power), and a variety of other applications areas.

Digital Signal and Data Processing: The very low power dissipation, very short switching times of superconducting tunnel devices can be used in a variety of data and signal processing applications. The very low power dissipation translates into very dense circuit and chip configurations for systems that can be extremely important for DoD applications. Examples are signal and data processing on platforms such as aircraft, satellites, and smart weapons.

A summary of S&T funding[18] for superconductivity technology is given in the following table.

Funding--Superconductivity ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
300	95	110	140	145	150	160

3. Utilizing the Technology (Examples)

a. Magnetic Sensors Utilizing Superconducting Quantum Interference Devices

The objective of this project is to field test two advanced-design superconducting gradiometer prototype systems. The first will be of all-thin-film design and operate at liquid helium temperatures with a 40 dB improvement in performance over the current system. The second device will operate at liquid nitrogen or neon temperatures with a 20 dB performance improvement over the current system.

Three paths are being explored to develop an advanced superconducting gradiometer. This approach provides ample time to develop technology options to select the most promising approaches and to reduce risk. The first is an LTS effort to develop an advanced-design thin-film, single-axis gradiometer to be used in environmental noise characterization; the second allows for the development of a five-axis LTS gradiometer and demonstration flight testing; the third pursues the development of an HTS gradiometer with demonstration field test.

During the first phase of the LTS single-axis development, advanced designs and system noise sources are studied and materials are characterized. This leads to selection of materials, fabrication technology, and device designs. In the next phase, these selected approaches are then fabricated and evaluated in an iterative process in order to refine techniques and produce optimal devices. Resulting devices are then integrated into a specially configured test dewar, and performance is demonstrated and characterized.

b. Power Applications of Superconductivity

The goal of this program is to develop high-power superconducting integrated power system for shipboard use. DoD is developing superconducting ship propulsion systems. A 3,000-horsepower LTS superconducting propulsion system has been demonstrated at sea. Critical-risk reduction issues must now be addressed to ensure the eventual fleet implementation of this technology. The combat environment places stringent

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18 Funding shown above for FY92 and subsequent years is highly speculative, in part because of the uncertainty in the time scale within which various applications are likely to become feasible, and in part because many projects involving superconductivity involve other technologies as well, and so the portion of the funding allocable to e[illegible] technology is often debatable. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

requirements for resistance to shock, vibration, and mechanical stress, which other power applications programs do not address. The major critical-risk reduction issues for this technology are the development of an efficient and reliable refrigeration system for a shock and vibration environment and the development of a more stable superconducting wire and magnet system.

DoD is also conducting an exploratory development project for selective power applications of superconductivity using LTS technology. The work will complement the planned advanced electric drive program and will focus on those critical-risk issues that need further exploratory development. These issues include development of advanced and more stable conductors (Al/NbTi and Cu/NbSn), which will significantly reduce the risk of suddenly losing superconducting performance or alternatively reduce the overall size and weight of rotating electrical machines; systematic study of magnet instabilities and their relation to conductor and magnet design; and development of turbine expander and Gifford-McMann refrigeration systems for improved reliability. Assessments of the effects of HTS materials will be made continuously; however, at the present time, superconductivity power applications of HTS seem far term because many materials problems must be overcome.

A DoD-funded engineering design study is underway to develop superconducting magnetic energy storage (SMES) system as a power source for ground-based lasers and load leveling applications for electrical utilities. This SMES system will store 20 MW-hours (72 gigajoules) in a solenoidal configuration of superconducting niobium-titanium alloy wires cooled by liquid helium.

The engineering test model will be about 100 meters in diameter and will demonstrate the feasibility of high-efficiency energy transfer. It will also demonstrate the multi-mode capability to discharge energy on a time scale of a few minutes for the ground-based laser applications or over several hours for electrical utility purposes.

c. Space Applications of High-Temperature Superconductivity

The objective of this project is to demonstrate the feasibility of incorporating the revolutionary technology of high-temperature superconductivity into space systems. The unique properties that superconductors exhibit can provide space surveillance, communications, navigation, weather, and weapon systems with performance capabilities far superior to those possible using conventional technologies. Superconducting technology can provide advances in spacecraft performance such as improved signal isolation with high-Q filters, dispersionless delay and transmission lines, detectors with multispectral sensitivity (from microwave to infrared, visible, and ultraviolet), infrared focal plane electronics, and traveling wave tubes (TWTs). Superconductors also offer improved spacecraft systems performance, such as quantum-limited detection (that is, as sensitive a detector as is theoretically possible), a sensitivity unattainable with any other technology.

The cryogenic equipment required for the operation of LTS materials impedes their use in the space environment. However, HTS materials, with operating temperatures above 80K, can utilize simple radiative cooling in space and hence make the use of superconductivity on spacecraft convenient for the first time.

Because HTS technology is so new, experimental data for modeling and making projections is limited. Space experiments are being carried out to reduce the development risk before considering HTS applications in operational space systems. Initial experiments will be ready for space tests within two to three years. The results of the space experiment will enable operational systems designers to evaluate both the benefits and possible problems of using superconducting components in their systems. The initial launch opportunity for the space experiments is FY91, but a FY92 launch is more likely.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

a. Low-Temperature Superconductors

Currently, US manufacturing capability for low temperature superconducting wire and supermagnets is highly developed. A lesser, but significant, manufacturing capability exists for LTS sensors and analog and digital electronics components.

b. High-Temperature Superconductors

High-temperature superconductors are not currently being manufactured, but rapid progress is being made at the research level. The HTS materials are typically in one of two forms: bulk material or thin films deposited on a substrate.

Bulk HTS are currently fabricated using a variety of techniques including melt-textured growth. Higher current density is achieved by controlling crystal size. At present, the maximum current density levels for the bulk HTS are ~17A/cm^2 at 77K with no magnetic field, which falls to ~4A/cm^2 in a magnetic field of 1 Tesla.

Thin HTS films are being fabricated by various techniques such as: laser ablation, magnetron sputtering, ion-beam evaporation, molecular-beam epitaxy, and chemical deposition. The maximum critical current densities achieved to date in single-crystal HTS films, fall in the range 10^6 to 10^7 A/cm^2 at 77K, which is much higher than achieved in bulk polycrystalline HTS materials.

2. Projected Manufacturing Capabilities

Bulk HTS materials are required in wire form for electromagnets; however, the brittle nature of HTS materials imposes limitations. Use is restricted to only magnets of very little curvature or, alternatively, techniques must be developed for fabricating electromagnets by forming them from compressed powders first and then firing them to final ceramic form.

For both bulk and thin-film HTS materials many fabrication obstacles must be overcome for them to be useful in their planned applications. The properties, particularly the superconducting properties, must be reproducible. Currently, these fabrication processes are performed on the research level and are not as reproducible as desired. Also, some HTS materials contain hazardous or toxic elements (such as thallium). The safe fabrication, use, and storage of these materials must be addressed and solved. Stability of materials is also a concern. Some of the elements used in these HTS compounds are moisture sensitive. Specific environmental conditions must exist during fabrication, storage, and use of these materials, and suitable passivating coatings must be developed.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

With federal funding, aspects of superconductivity R&D are being pursued in US universities, industry, and government laboratories. Federal support is centered primarily in DoD, DoE, NASA, the National Science Foudnation (NSF), and the Department of Commerce (DoC). DoD supermagnet-based applications may be expected to benefit significantly from the extensive DoE efforts on supermagnets. However, DoD interests in superconducting sensors, analog electronics, and digital electronics are being addressed at only very modest levels in other agencies and industry. Thus the US competitive position in these important areas appears to be highly reliant on the success of DoD efforts.

2. R&D in the Private Sector

In the United States, the private sector provides about half the amount of funding for superconductivity R&D as that provided by the federal government. A few large companies (in the communications, computers, and chemicals industries) are most active, and they depend only little, if at all, on federal funds for their superconducting activities. More modest privately funded superconductivity R&D efforts are underway in other companies, usually to augment of federally supported activities. These companies include large defense, aerospace, electrical, and electronic companies; well-established small companies that market superconducting wire, magnets, and instruments; and small venture-capital firms that have recently been established in attempts to capitalize on the recent advances in high-temperature superconductivity. Together these private-sector-funded activities are of great benefit to the overall national capability in superconductivity R&D.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

The table on the following page provides a summary comparison of United States and other nations for selected key aspects of the technology. Ongoing international research and development indicates potential international capabilities to contribute to United States challenges and goals including:

- Increased transition temperature of HTS
- Development of material processing and fabrication techniques for HTS applications
- Effective integration of superconducting elements with semiconductors
- Development of superconducting naval power/propulsion system.

Summary Comparison--Superconductivity

Selected Examples	USSR	NATO Allies	Japan	Others
Increase transition temperature of HTS	▨▨	□□	□□□	□□ China, Switzerland □ Brazil, Israel
Develop material processing and fabrication techniques for HTS applications	▨▨▨	□□	□□□□	□□ China, Switzerland □ Brazil, Israel
Effective integration of superconducting elements with semiconductors	▨	□□	□□□□	
Develop superconducting naval power/ propulsion system	▨▨▨	□□	□□□	□
Overall [a]	▨▨	□□	□□□□	See above for niche capabilities.

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

The United States and Japan share a worldwide lead in this technology. Japanese technology could make significant contributions, especially in digital electronics, where Japan enjoys a significant lead. Opportunities may, however, be limited by trade and economic obstacles on both sides. NATO research, while generally behind that of the United States and Japan, is extensive and may offer opportunities for cooperative research in a number of areas.

Overall Japan and the United States are on a par, but Japan has a significant lead in digital superconducting devices and systems. Unlike the United States, where Josephson junction (JJ) digital electronics research was all but terminated in the early 1980s, Japan has a continued research effort in this area. Moreover, they have apparently developed techniques to overcome the long-term stability problems which accounted in part for the abandonment of this technology by US industry. Supported by Ministry of International Trade and Industry (MITI) programs, Japan has continued to develop LTS digital logic and memory assemblies for computing applications. Component densities (20,000-30,000 JJ chips with digital logic and 4K memories), while low, have been steadily increasing. Japan's organization and industrial emphasis is on materials processing as a key enabling technology for all applications. Japanese industrial research is notable for the number of companies conducting vigorous, internally funded, high-quality efforts, suggesting a potential for rapid adoption of HTS products in Japan. In the long term, this emphasis may position Japanese industry for a sustained lead in this area.

While Japan and the United States are expected to remain the leaders in superconductivity, many other countries are active in the field, and NATO will have significant capabilities by 1991. Europe has traditionally been strong in basic research, but has trailed in applications with the exception of narrow niche areas such as magnets and cables. Companies in the UK and FRG are leading producers of magnets for medical imaging. In addition, the CERN supercollider project is providing impetus to these areas of research.

Virtually all European nations (most notably the UK, Italy, and the FRG) have national programs in HTS involving both government and industry. For example, the UK Atomic Energy Authority has established a collective search for new superconducting materials. This program is patterned after a successful program addressing electronic ceramics in the early 1980s and will involve standardized automated testing of materials. As yet, clear patterns of international cooperation at the governmental levels (comparable to the Joint European Submicron Silicon Program or the European Strategic Program for Research in Information Technology) have not emerged. At the research activity level, however, international ties are being forged, offering the promise of a better integrated and fruitful NATO effort in the future. For the near term, however, cooperative efforts with NATO allies will be limited to efforts in which the United States takes the technical lead, with the allied participants providing support in specific niche areas.

2. Exchange Agreements

DoD-sponsored exchange activity in the area of superconductivity has been modest, but significant. The NATO program in physics and electronics has provided a mechanism for exchanges of fundamental scientific information. The Technology Cooperation Program (TTCP) groups in basic material and electronic materials provide several potential mechanisms for cooperative exchanges in fundamental science, and some limited exchange of information may occur for specific applications of the technology to instrumentation and military electronics. However, superconductivity is not explicitly identified as a topic of research.

20. BIOTECHNOLOGY MATERIALS AND PROCESSES

A. DESCRIPTION OF TECHNOLOGY

Owing to the discovery and exploitation of the genetic mechanisms that control living organisms, biotechnology has emerged as a critical technology. It is now possible to engineer microbial, plant, and animal cells to act as factories for the synthesis of existent or new materials at substantially enhanced rates and efficiency. This technology has the potential for resolution of DoD operational and logistical problems in both medical and non-medical arenas. In the medical arena, biotechnology makes possible new vaccines and therapies, and in the non-medical arena it is leading to new structural materials, critical chemical intermediates, and practical solutions to waste site remediation. Many of the products have significant civilian application and have garnered widespread interest. DoD has become recognized as an international leader in materials biotechnology. Continued exploitation of biotechnology can provide new, more efficient and cost-effective products for state-of-the-art military systems and provide a range of benefits of great economic importance.

Critical Technology Challenges for Biotechnology

• Materials • Processes • Sensors

B. PAYOFF

1. Impact on Future Weapon Systems

The effect of biotechnology on the military capabilities of the U.S. in the non-medical arena can lead to the development of a vast array of products, processes, and technologies including new or improved light-weight, high-strength polymers and composites for construction of aircraft, protective clothing and gear, and other military equipment; sensors for detecting chemical, biological and toxic agents; molecular switching and other microelectronic devices; bioadhesives; environmentally safe antifoulant coatings; general and specialty elastomeric compounds; high-speed specialty lubricants; and surfactants and enzymes for use in decontamination and cleaning operations. Bioprocesses will provide some of these products as well as conventional materials from non-petroleum-based feed stocks.

In addition, the DoD has a significant hazardous waste problem and the enormous cost of the required remediation of DoD sites has received recent public attention. This cost cannot be deferred because compliance is a legal requirement, and use of conventional methods could significantly affect DoD operational resources. Biotechnology offers a viable, cost-effective alternative for the permanent solution of many of the DoD hazardous waste problems by using microbial or catalytic methods to degrade wastes and explosives, bioengineered polymers for radionucleide recovery, biodegradable lubricants, and anti-fouling paints.

Medical biotechnology is not the focus of this description, yet it will support military operations by providing new and more potent broad spectrum vaccines and therapeutics to protect against endemic and epidemic diseases encountered in deployment areas. Other products will include preventive and casualty care pharmaceuticals such as tissue compatible adhesives, bone replacements, and rapid wound healing promoters. The development of a low-cost, artificial blood substitute is another important goal of the biotechnology program.

Some specific goals and payoffs anticipated from the DoD materials biotechnology initiative are given in the table on the following page.

2. Potential Benefits to the Industrial Base

The ability of certain organisms, or enzymes derived from these organisms, to perform specific chemical transformations under a wide range of conditions can be turned to useful advantage to produce products with unique applications or to solve hazardous waste and metal extraction problems. Bioprocesses have the intrinsic advantage of requiring far less energy and therefore can be considerably less costly. They are also less environmentally damaging and proceed with greater speed, specificity, and selectivity than do conventional processes. Additionally, recombinant DNA technology can be used to tailor organisms to perform specific tasks or to manufacture products that would be difficult or costly to obtain using conventional methods.

Biotechnology offers numerous dual-use applications. In particular, DoD investment in the biomaterials R&D area has already begun to produce products that benefit the industrial base. Examples are plastic polymers now commercially produced and the spin-off invention and development of a revolutionary process for the manufacture of sub-0.5 micron feature definition microelectronic devices. This patented process has now been licensed to the major US supplier of microlithography materials with sublicenses being developed with the major US semiconductor companies. Another important example is the transition of fundamental bioprocessing mechanisms and systems into the agricultural industrial base for the production of materials in crops.

Specific Goals and Payoffs--Biotechnology Materials and Processes

Goals	Payoffs
Biosensors	
• Optical-based microsensors • Function-based microsensors • Biomolecular ion detector	• Improved real-time detection and identification of toxins, exposives, and drugs • Improved non-acoustic undersea surveillance
Bioprocesses	
• Waste site bioremediation	• Low-cost, permanent solution for persistent toxic substances
• Biopaintstripping	• Elimination of hazardous solvents for removal of paint from aircraft
• Enzyme decontamination and surfactants	• Enhanced decontamination and cleaning agents
• Biomining	• Enhanced recovery of strategic metals from low- grade ore
• Synthesis of energetic compounds	• Lower cost and improved safety for high-energy materials
• Degradation of energetic compounds	• Low-cost, environmentally safe disposal
Biomaterials	
• Recombinant derived fibers	• Improved light-weight, high-strength materials
• Biosynthetic polymers	• Low-cost, low-weight, high-strength organic matrix composites for aircraft
• Catalytic polymers	• Self-decontaminating materials for individual and collective protection
• Bioelastomers	• Seals, gaskets, coatings with better chemical and mechanical properties
• New antifoulants	• Environmentally safe coatings for ships, buildings, and bulkheads with improved performance
• Bioadhesives	• Unique mechanical and biocompatibility properties
• Biosynthesized lubricants	• Low-cost, high-performance lubricants for aircraft and missiles
• Microencapsulation	• Encapsulated, biocompatible acute care blood substitute
Bioelectronics	
• Lithography	• Low-cost microcircuit manufacturing
• Thin-film, self-assembling molecular arrays and switches	• Increased circuit density and speed with decreased size; three-dimensional logic capability
• Improved metallized biotubule fabrication and composites	• High-power microwave and energy storage devices

C. S&T PROGRAMS

1. Milestones

Milestones--Biotechnology Materials and Processes

Technical Area	By 1995	By 2000	By 2005
Biosensors	• Second-generation biodetection dipsticks • First-generation receptor-based biosensor for biodetection	• Robotic CB detector for specific threats • Real-time receptor-based all biodetector	• Robotic, real-time, receptor-based all agent CB detection system
Bioprocessing • Bioremediation	• Phase I restoration of soil contaminated with fuels and nitroaromatics • Fully operable biotreatment systems for PCBs and TCE in ground water • Pilot plant for degradation of ammonium perchlorate rocket motors	• Fully operable modular systems for soil restoration • Completion of PCB and TCE contaminated ground water and rocket motor degradation programs	• Completion of prior remediation targeted waste sites
• Biopaintstripping	• Scale-up for batch processing for pilot plant testing on aircraft	• Complete self-contained bio-stripping system for aircraft	• Additional applications of bio-stripping to other DoD equipment and facilities
• Biomining	• Batch recovery of gallium and other strategic metals from low-grade ores	• Immobilized biochelators for industrial end stream recovery	• Advanced high rate up- and downstream processing systems
• Energetics Synthesis	• Room-temperature synthesis of some nitrate esters and aliphatic nitro-compounds	• Full range of nitrifying and de-nitrifying biotech products	• Novel, high-energy propellants and explosives
Biomaterials • Fibers	• Invitro synthesis of silk(s) fiber(s) or subunits	• Scaled up solid-state synthesis of fibers	• Other high-strength fiber materials developed
• Polymers	• Pathways cloned and scaled up for several thermoplastics and composite intermediates	• Pilot plants for thermoplastics and intermediates	• Full production and application of biosynthesized plastics and copolymers
• Elastomers	• Variant organism will produce identified product and product characterization and cloned synthesis	• Material and production optimization; initial pilot plant syntheses	• Full production of gaskets, coatings, shock absorbers
• Adhesives	• Scale up of bioadhesives FDA approval for IR&D for human applications	• Large-scale production for operational applications; human use applications	• Final approval for casualty care applications
• Bioelectronics	• Pilot plant production of metalized tubules: EMI coatings field tested • Primitive switching devices • Primitive self-assembling devices	• Structural microwave composites • EMI coatings deployed in operational systems • Advanced switching devices • Advanced working devices	• High-power microwave devices • High-density circuitry • Systems integration of self-assembling devices
• Ceramics	• Identify cost-efficient methods for producing ceramics	• Key control mechanisms determined	• Process for nanophase ceramic and organic/ceramic composite production
Technology Demo • Biomaterials	• Polymer and copolymers produced in sheets and belts	• Scaled-up testing of polymers in materials applications	
• Bioremediation	• Site demo-TCE degradation • Site demo-nitroaromatic compositing	• 100% scale up • 100% scale up	
• Bioadhesives	• Binding strength demo • Mechanical and physiological strength demo • Subhuman eye perforation repair	• Wound repair efficacy • Composite repair and manufacturing applications demonstrated • Human use tissue and bone repair efficacy	

2. Developing the Technology

DoD biotechnology is a multi-component program with the main goal of providing new materials and processes in support of mission and operational requirements. A technology base has been developed for using biological systems, their paradigms, and their products for application to military systems and problems. The principal areas are listed in the milestone table and discussed in the following paragraphs with regard to present status and future efforts required for demonstration of utility, applications ready for full-scale engineering development within the next decade and where applicable, the relationship to other related basic technology areas.

The biosensor program will develop automated sensors that will couple highly specific biomolecules for chemical recognition with fiber optic and electronic technology. The program is divided into the development of optical microsensors that detect the binding of an analyte by an antibody or receptor at the surface of a fiber optic probe and systems in which receptors in a synthetic lipid membrane, attached to the surface of a silicon chip, control the gating of ion channels in response to a physiologically active agent.

The bioprocessing program is based on the remarkable ability of microorganisms to evolve, adapt, and perform biochemical transformations over a wide range of conditions. The ability of certain organisms or enzymes derived from these organisms, to perform specific chemical transformations under ambient conditions can be turned to useful advantage to produce products with unique military applications or to solve DoD's hazardous waste and strategic metals problems. The intrinsic advantage that bioprocesses offer over conventional means of achieving chemical transformations is that they are usually more favorable energetically. Consequently they are less costly, less environmentally damaging, and occur with greater speed, specificity and selectivity. Furthermore, with the advent of recombinant DNA technology, it is now possible to tailor organisms to perform specific tasks or to manufacture products that would otherwise be difficult or costly to obtain using conventional synthetic routes.

The primary goal of the bioremediation and hazardous waste reduction effort is to develop workable field solutions for cleaning up hazardous wastes located on military bases using a biodegradation or biotransformation approach.

Current methods of paintstripping use dangerous organic solvents or plastic media blasting that are environmentally hazardous or potentially damaging to aircraft structural integrity. A different approach that is being tested incorporates enzyme degradation. An enzymatic system does not require strict containment, may be recycled, and is environmentally safe. Completed work has shown that controlled and safe biodegradation of paint is possible.

Bacterial leaching or bioleaching is a hydrometallurgical process for making metals soluble and separating them from their mineral matrices. The principal benefits of bacterial leaching are low operating costs and mitigation of air and water pollution. The current objectives are to identify microorganisms that bioaccumulate strategic metals, determine the mechanisms that govern the bioaccumulation or chelation processes, immobilize chelators onto an inert carrier so that specific metals can be selectively recovered, and develoop suitable scale up procedures.

The isolation, characterization and modification of enzymes, biocatalysts, and surfactants for use in military decontamination operations remains an objective of the biotechnology program. Two principal classes of contaminants are the focus of this program, chemical agents (organophosphates and mustards) and biological agents (e.g., Ricin). Enzymes capable of degrading both classes of agents have already been identified and partially characterized.

Materials research includes microbial synthesis of chemical intermediates for aircraft composite materials, macromolecules for the encapsulation of hemoglobulin, thin film materials for electronics, macro-molecules for the control of corrosion and marine fouling, self-assembling structures for microelectronics, adhesives for medical and non-medical applications, and new elastomeric compounds and biomolecules for use as lubricants.

Methods for in-vitro production of spider and worm silks, which are fibrous biopolymers having tensile strength greater than steel and elasticity greater than wool, have been examined, and cloning of the genes responsible for the spider polymer has been accomplished. Work on fiber assembly leading to scale-up is underway. In the case of elastomers, polyhydroxyalkanoate strips have now been produced in small quantities. They have physical and mechanical properties typical for high-quality elastomers, yet are biodegradable in their native form. Studies are underway to provide a nondegradable variety. Development of other degradable and nondegradable thermoplastics using the molecular biology approaches will continue. In the composite arena, work has begun on identifying biosynthetic pathways for the preparation of acetylenic groups and chemical intermediates. It has been shown that these compounds can be produced using biotechnology methods and therefore, new or less costly aerospace structural composites may become available. Benzene can be converted, through microbial catalysis, to an intermediate product useful in the production of polyphenylene. This substance is used at 600- to 700° F and can be produced by biotechnology methods for less than $10 per pound; other materials with the same thermal performance characteristics cost hundreds of dollars per pound to produce. R&D efforts will continue to identify and examine metabolic pathways or organisms that can provide chemical intermediates for use in resin matrix and carbon-carbon composites.

In the area of bioadhesives, a mussel adhesive has been defined, characterized, and manufactured. It forms strong, durable bonds with a variety of surfaces, cures rapidly, and is nontoxic. It also has applications in gluing tissues and in replacing eye lenses; the latter operation has been performed on animals. Genetic manipulation for engineering other desired material properties has been initiated for this and other bioadhesives. In the area of lubricants, a material has recently been isolated from a primitive thermophilic organism that has an unusual structure and holds promise as an inexpensive, high-temperature, chemically stable lubricant or additive. Wear tests and other initial characterization studies are underway.

In bioelectronics, DoD efforts focus on optical storage and switching devices using biomolecules and self-assembling microstructures. (All but the last efforts are in the basic research stages.) A new ultra-high resolution microlithography process, based on biomolecular research on biotubules, has been transferred to industry and is the subject of a cooperative R&D agreement between an industrial concern and a DoD laboratory. The process has been used for prototype semiconductor devices with features less than 0.5 micron. This process promises to be technologically and economically important to the United States.

A summary of total S&T funding[19] for this technology is given in the following table.

Funding--Biotechnology Materials and Processes ($M)

FY86-90	FY91	FY92	FY93	FY94	FY95	FY96
451	100	100	100	105	110	115

3. Utilizing the Technology

The fine chemicals and pharmaceutical industries have already incorporated biotechnology to produce critical chemical intermediates and drugs. Many of the pharmaceutical products are used in Service programs for both R&D and patient care. Bioprocessing methods are now being utilized in several DoD environmental restoration projects; these involve the bioremediation of munitions and jet fuel contaminated soil and solvent contaminated aquifers.

Bioadhesive, now commercially produced, is being used in the science and technology programs of two Services, for use as an adherent in tissue grafting studies and bone repair. Biotubules is being incorporated in antifouling paint for the prevention of fouling of ship hulls. Several biopolymers are being tested and modified for proposed use in operational systems including laser eye protection.

D. RELATED MANUFACTURING CAPABILITIES

1. Current Manufacturing Capabilities

A review of activities in this area of biotechnology indicates that the major R&D effort is still in the basic or applied research stages. Presently, there is some domestic manufacturing capability in the use of biomining techniques for the recovery of copper and some rare metals and in the bioremediation area. There is also limited production, via solid-state synthesis, of (mussel) bioadhesives now being sold commercially. There is moderate capability in the manufacturing of biosurfactants and degreasers. In general, US fermentation technology will have to expand to meet future needs. University training programs will also have to expand to meet additional demands.

2. Projected Manufacturing Capabilities

No plans for establishing manufacturing capabilities in materials biotechnology areas of importance to the military are known to exist. However, in the medical diagnostics, pharmaceutical, and agricultural biotechnology areas there is strong interest

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19 Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

and support from the private sector because of the great commercial potential. Private industry is expected to develop a large portion of this technology, thus bypassing the traditional government-sponsored manufacturing technology programs. DoD is establishing techniques for heat stable enzymes used for detecting chemical and biological agents and manufacturing receptor proteins.

In areas with less commercial potential and that are oriented primarily toward military applications, government-sponsored manufacturing technology will need to be provided. These areas include the biosynthesis of systems-specific polymers, fibers, elastomers, and lubricants. A specific example is the biosynthesis of hydroxyphenylacetylene, which will provide a low-cost intermediate for acetylene-terminated resins. This work is being conducted with technology base funds, and transition opportunities to engineering development and manufacture will have to be provided through DoD support.

Other investments relate to future chemical and biological detection equipment, which will depend on biological sensor materials that will provide tremendous improvement in agent sensitivity and specificity. Currently, these biosensor materials are available only in small research quantities. Due to the limited availability of these materials and the pervasiveness of proprietary processes, their costs are prohibitively high ($1,000 to $10,000 per gram). To reduce the costs and provide military-required quantities, manufacturing technology projects are planned to develop large quantity production processes for the types of biomaterials needed.

E. RELATED R&D IN THE UNITED STATES

Federal and private sector spending on biotechnology R&D exceeded $50 billion in 1988. Of this, about $2.7 billion was the result of federal investment. Most R&D within the private sector was performed in the pharmaceutical and agricultural areas. The National Institutes of Health provided 84 percent (or $2.3 billion of the federal spending. DoD was the second largest spender, followed by the National Science Foundation (NSF), DoE, the U.S. Department of Agriculture (USDA), the Environmental Protection Agency (EPA), the Food and Drug Administration (FDA), and the National Institute for Science and Technology (NIST). DoD provided approximately $12 million for university-supported research and an additional $4 million for the University Research Initiative, a program for the re-equipping of major instrumentation items. DoD also provided about $1 million through the small business innovative research (SBIR) program.

In the areas of biomaterials and bioprocesses, most industry and university investment has been through government sponsorship, particularly the Offices of Scientific Research of the three Services and the Defense Advanced Research Projects Agency (DARPA). Within the DoD program, this expenditure amounts to about 75 percent of the funds being spent in these areas. Non-government-supported industrial activity has been increasing in the critical chemicals area.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

This section assesses the relative position of various countries with respect to biotechnology, taking into account strengths and weaknesses in basic research and development of products with commercial and military potential. Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Enhanced efficiency of quantity production of biomaterials (including DNA amplifiers capable of dealing with small concentrations of target sequences)
- Development of DNA libraries for militarily useful biomaterials
- Development of empirical data bases characterizing the performance of biomaterials in specific applications
- Application of biomaterials to real-time sensing of chemical and biological warfare (CBW) agents.

Because of the pervasiveness of biotechnology in health and agriculture, there is virtually universal interest and activity in these fields. Cooperative opportunities will exist with most of the NATO countries and many other free world nations as well.

The United States is recognized as the world leader in biotechnology. However, the United States will face considerable competition from Japan, whose strengths include applied biotechnological research, interaction among companies, a diversity of programs, a long-term approach to biotechnology, and strong government support. Biotechnological research and development covers a broad range of areas and includes pharmaceuticals, specialty and bulk chemicals, energy applications, environmental protection, bioelectronics, materials development, and biosensors. Japan is considered the world leader in biosensor research and development.

Biotechnological research in Japan is carried out by government, industry, and academia. Industrial efforts involve companies with a history of R&D in the biological sciences as well as companies that are primarily involved in other areas but are branching into biotechnology. Many Japanese companies look to US biotechnology companies for collaboration and technology transfer.

Although currently behind the United States and Japan, many European countries such as the UK, FRG, and France are doing well in various areas of biotechnology. Other European countries, although not as strong in biotechnology, are also developing programs. Italy, for example, has adopted a National Research Plan for Biotechnology and a National Program for Bioelectronic Technology Research.

Biotechnological research and development in Europe covers an extensive range including pharmaceuticals, agriculture, biosensors, bioelectronics, materials development, and environmental protection. Research is carried out by government laboratories, academia, and industry. Industrial efforts have been concentrated in the larger pharmaceutical and chemical companies, although smaller biotechnology companies are also found in Europe, especially in the UK. The larger companies have tended to look to US biotechnology companies for collaboration.

Summary Comparison--Biotechnology Materials and Processes

Selected Examples	USSR	NATO Allies	Japan	Others
Enhance efficiency of quantity production of biomaterials (including DNA amplifiers capable of dealing with small concentrations of target sequences)	▨▨	□□□	□□□□	Various Countries □□
Development of DNA libraries for militarily useful biomaterials	▨▨	□□□	□□□	□□
Development of empirical data bases characterizing the performance of biomaterials in specific applications	▨▨	□□□	□□□	□□
Application of biomaterials to real-time sensing of CBW agents	▨▨	□□□	□□□□	□□
Overall[b]	▨▨	□□□	□□□□	□□[a]

[a] Because of the pervasiveness of biotechnology in fundamental health and agricultural industries and the dissemination of technology, research in this field is occurring virtually worldwide.

[b] The overall evaluation is a subject assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of USSR relative to the United States		Capability of others to contribute to the technology	
▨▨▨▨	significant leads in some niches of technology	□□□□	significantly ahead in some niches of technology
▨▨▨	generally on a par with the United States	□□□	capable of making major contributions
▨▨	generally lagging except in some areas	□□	capable of making some contributions
▨	lagging in all important aspects	□	unlikely to have any immediate contribution

The FRG government is subsidizing more than 40 research projects. These long-term, high-risk projects would not be possible without some governmental aid. The program was begun in 1985 and, as of 1987, 16 companies in West Germany were taking part. More than $10 million was budgeted in 1987 for this program.

In the Netherlands, the founding of Groningen Biotechnology Center in 1981 combined 10 biotechnologically oriented research groups at Groningen University. Research is conducted in industrial bioorganisms, fine chemicals, industrial enzymes, and environmental biotechnology (treatment of waste).

Many European universities and institutes are active in biotechnology. Cranfield Biotechnology Center at the Cranfield Institute of Technology is especially noted for research on biosensors. The Institute has developed rapid methods for microbial contamination monitors and provides consulting services to industry, including bioaudits to assess contamination in factory work areas.

To help strengthen European efforts in biotechnology, a number of collaborative programs have been established. The European Communities Bridge (Biotechnology Research for Innovation, Development, and Growth in Europe) program has recently been planned and would replace the Biotechnology Action Program (BAP) that began in 1985. The BAP followed the Biomolecular Engineering Program, which was set up in 1982. Another program supporting biotechnology is the European Research Coordination Agency (EUREKA) program, which involves 19 countries.

The Soviet Union is currently involved in a major biotechnology program. Efforts in biotechnology cover a range of areas including agriculture, pharmaceuticals, bioelectronics, and applications in space. Although the overall Soviet biotechnology capabilities are behind the West, the Soviets are conducting research in some areas that is at least equal to Western efforts.

The Soviet Union has an extensive program in biotechnology research, which is concentrated in a relatively small number of R&D centers located primarily in Moscow, Pushchino, Novosibirsk, and Leningrad. Although only a few Soviet researchers are believed to be performing research at the level of their counterparts in the West and Japan, others are not far behind. Moreover, in at least one important area, biotechnological research in space, the Soviets hold an advantage based on their long-term space station activity.

East Germany is emphasizing training in biotechnology at all universities, targeting interdisciplinary research and development areas, supporting collaborative projects between academic and industrial entities, expanding and updating laboratory facilities, and building new laboratories with modern equipment. East Germany's overall program is to achieve a threefold increase in biotechnological applications by 1990.

Since much of the research in this field is published in open literature, the USSR has not faced restrictions in accessing a large body of scientific knowledge. For example, in 1982 a conference was held in Finland on the use of computers and microprocessors on process models and control of biotechnology. Topics covered included precise measurement technology and sensors, process models of bioreactors, and adaptive control in microbiological processes. Conference proceedings were published in a Russian journal of microbiology.

Western biotechnology organisms and products are readily available to the USSR. The Soviet laboratories at Biogen have Western biotechnology equipment, including centrifuges, chromatography equipment, spectrophotometers, culture media, automatic pipetters, personal computers, and scintillation counters. In the past two years the Soviets have also purchased amino acid analyzers, hollow-fiber cell culture systems, automated fermentation systems, automated DNA sequencers, and "gene machines" from Western companies.

2. Exchange Agreements

There is a high level of exchange activity in the area of biotechnology. The NATO Defence Research Group (DRG) program in defense applications of human and biomedical research provides a mechanism for exchanges of fundamental scientific information.

The Technology Cooperation Program (TTCP) provides a number of mechanisms for exchange in a range of applicable activities. Specific topics under TTCP include some nine active programs in the area of nuclear/biological/chemical (NBC) warfare. Topics of direct interest range from the general area of NBC defense to specific topics such as filter performance and toxicological testing of agents affecting filter performance. Also included in this group is detection and monitoring of chemical and biological agents.

The Army has a number of related exchanges, primarily with NATO, but also with other nations, covering CBW defense topics. Here a primary interest is in materials and equipment for protection and techniques for detection and remediation or decontamination of CBW agents. In addition, biotechnology is an underlying technology for a number of other applications covered by international exchange programs. These cover such topics as development of fuels and lubricants, ordnance/energetic material disposal, and potential uses as structural adhesives.

Appendix B

CONGRESSIONAL REQUIREMENT FOR A CRITICAL TECHNOLOGIES PLAN

(Reproduced from PL 101-189, November 29, 1989)

EXCERPTS FROM NATIONAL DEFENSE AUTHORIZATION ACT FOR FISCAL YEARS 1990 AND 1991: ANNUAL DEFENSE CRITICAL TECHNOLOGIES PLAN (PL 101-189)

(b) ANNUAL DEFENSE CRITICAL TECHNOLOGIES PLAN.—(1) Chapter 148 of title 10, United States Code, is amended by adding at the end the following new section:

"§ 2508. Annual defense critical technologies plan

"(a) ANNUAL PLAN.—(1) The Secretary of Defense shall submit to the Committees on Armed Services of the Senate and House of Representatives an annual plan for developing the technologies considered by the Secretary of Defense and the Secretary of Energy to be the technologies most critical to ensuring the long-term qualitative superiority of United States weapon systems. The number of such technologies identified in any plan may not exceed 20. Each such plan shall be developed in consultation with the Secretary of Energy.

"(2) In selecting the technologies to be included in the plan for any year, the Secretary of Defense and the Secretary of Energy shall consider both product technologies and process technologies, including the technologies identified in the most recent biennial report submitted to the President by the National Critical Technologies Panel under title VI of the National Science and Technology Policy, Organization, and Priorities Act of 1976.

"(3) Each such plan shall cover the 15 fiscal years following the year in which the plan is submitted.

"(4) Such plan shall be submitted not later than March 15 of each year and shall be submitted in both classified and unclassified form.

"(b) PRIORITIES AND FUNDING.—Each plan submitted under subsection (a) shall—

"(1) designate priorities for development of the technologies identified in the plan; and

"(2) specify the funding requirements of the Department of Defense, the Department of Energy, and other appropriate departments and agencies of the Federal Government for the development of the technologies identified in the plan for the five fiscal years following the year in which the plan is submitted.

"(c) CONTENT OF PLAN.—Each plan submitted under subsection (a) shall include, with respect to each technology identified in the plan, the following:

"(1) The reasons for the selection of that technology, including—

"(A) a discussion of the consideration given to the most recent biennial report submitted to the President under title VI of the National Science and Technology Policy, Organization, and Priorities Act of 1976; and

"(B) the relationship of the technology to the overall science and technology program of the Department of Defense and the long-term funding strategy associated with that program.

"(2) A designation of the lead organization within the Department of Defense or the Department of Energy responsible for the development of the technology.

"(3) A summary description of the lead organization's plan for the development of the technology, including the milestone goals.

"(4) The amounts contained in the budgets of the Department of Defense, the Department of Energy, and other departments and agencies for the support of the development of such technology for—

"(A) the five preceding fiscal years; and

"(B) the fiscal year beginning in the year in which the plan is submitted; and

"(C) each fiscal year thereafter for which the Secretary of Defense, with respect to the Department of Defense, and the Secretary of Energy, with respect to the Department of Energy, has prepared a budget.

"(5) A comparison of the positions of the United States and the Soviet Union in the development of that technology.

"(6) The potential contributions that the allies of the United States and other industrialized nations can make to meet the needs of the United States and its allies for that technology.

"(7) A comparison of the extent to which the United States has access to research conducted on such technology in allied nations and other industrialized nations with the extent to which such nations have access to research conducted in the United States on such technology and a discussion of the effects of any imbalance in such access on development of that technology.

"(8) With respect to the development of such technology—

"(A) a comparison of the relative positions of the United States and other industrialized countries that are prominent in the development of such technology;

"(B) the trends in the relevant industrial bases of such countries;

"(C) the competitiveness of the United States industrial base supporting research in, and the development and use of, such technology;

"(D) the extent to which the United States should depend on other countries for the development of such technology; and

"(E) the extent to which action should be taken by the Federal Government to maintain and improve—

"(i) research efforts in the United States; and

"(ii) the industrial base supporting such efforts.

"(9) The potential contributions that the private sector can be expected to make from its own resources in connection with the development of civilian applications for such technology.".

(2) The table of sections at the beginning of such chapter is amended by adding at the end the following new item:

"2508. Annual defense critical technologies plan.".

Appendix C

SUMMARY OF CRITICAL TECHNOLOGY CHALLENGES

SUMMARY OF CRITICAL TECHNOLOGY CHALLENGES

To describe each critical technology, a set of technical activities that collectively describe that technology must be identified. These activities are listed in the following table (in column two) and expressed in terms of technology challenges; some are phrased in terms of processes.

The last column summarizes the defense role. The importance of defense support relative to non-defense support of each technology is indicated by circles: a black circle indicates that the development of the technology is heavily dependent on defense funding, a shaded circle indicates that defense and non-defense funding are comparable, and a white circle indicates that defense relies heavily on industry for the development of the technology.

Table C-1. Summary of Critical Technology Challenges

Technology	Technology Challenge	Defense Role	
1. Semiconductor Materials and Microelectronic Circuits	• Low-volume production techniques for sub 0.2 micron devices • Radiation hardening • CAD for complex circuits • Sub 0.3 micron production lithography • Packaging/interconnect • Compound semiconductor materials preparation	○	• Focus R&D on unique military needs • Support generic R&D in faltering areas
2. Software Producibility	• Reusable software • Automatic software generation • Secure and trusted software • Software for distributed systems • Software and system engineering environments • Real-time/fault-tolerant software	○	• Provide R&D support for unique DoD software • Lead US efforts in metrics and tools
3. Parallel Computer Architectures	• Integration of heterogeneous processor elements • Architectural design • Integration of special-purpose systems • Algorithms, tools, and languages • Specialized compiling, operating, and debugging approaches	●	• Government-supported R&D leads US effort • Component technology from commercial sources
4. Machine Intelligence and Robotics	• Knowledge acquisition and representation • Automated reasoning • Man-machine interface • Training • Articulated mechanical devices	○	• Exploit extensive commercial R&D for unique needs • Rely on commercial hardware
5. Simulation and Modelling	• Complex battle management • Training in complex military environments • Industrial design and production	◐	• DoD R&D on military weapon systems and environments • Rely heavily on commercially available computing hardware

(Continued)

Key: ● DoD/DoE R&D leads the US effort--DoD/DoE applications drive the technology ◐ DoD/DoE R&D comparable to industry and other agencies--many non-defense applications ○ DoD/DoE heavily reliant on industry or other agency R&D--non-defense applications dominate

Table C-1. Summary of Critical Technology Challenges (Continued)

Technology	Technology Challenge	Defense Role	
6. Photonics	• Ultra low-loss fiber optics • High-power laser diodes and arrays • High-speed networks with fiber optic backplane • High-speed, low-energy switches • High-performance spatial light modulators • High-speed optical inter-connects • Opto-electronic integrated circuits • Nuclear-hardened components	◐	• Exploit extensive commercial R&D • Lead US R&D effort in laser diode arrays • Focus on military-unique applications
7. Sensitive Radars	• Wide bandwidth radar • Laser radar • Sensors for non-cooperative identification • Miniature synthetic aperture radars	●	• DoD leads major R&D efforts • Exploit specialized components and software of industry
8. Passive Sensors	• Passive threat warning • Microwave/millimeter-wave radiometry • Passive coherent radar • Advanced thermal imagers • IR search/track • IR focal plane arrays • Compact antennas • Superconducting sensors • Fiber optic sensors • Large volumetric acoustic arrays • Sensor integration	●	• DoD leads major R&D efforts • Exploit specialized components and software of industry
9. Signal Processing	• Matched filter techniques • Model-based approaches • Artificial neural networks • Hybrid optical-digital techniques • Signal processing for phased arrays • Algorithm development • Training set development	◐	• Aggressive R&D on military-unique applications • Lead US R&D effort in algorithms and performance evaluation

(Continued)

Key: ● DoD/DoE R&D leads the US effort--DoD/DoE applications drive the technology ◐ DoD/DoE R&D comparable to industry and other agencies--many non-defense applications ○ DoD/DoE heavily reliant on industry or other agency R&D--non-defense applications dominate

Table C-1. Summary of Critical Technology Challenges (Continued)

Technology	Technology Challenge	Defense Role	
10. Signature Control	• Design for low observability • Radar-absorbing materials • IR signature reduction • Acoustic quieting • Visual and UV signature reduction • Deceptive emissions and decoys	●	• Provide R&D supporting full range of military needs
11. Weapon Systems Environment	• Underwater acoustic propagation • High-resolution environmental remote sensing • High accuracy environmental prediction • Scene models for system design and evolution	◕	• Integrated effort of empirical data collection and modeling
12. Data Fusion	• Man-machine interface • Distributed, real-time systems • Algorithm development • Multi-level security • Expert systems development	●	• Lead US-wide R&D effort in man-machine interface aspects (e.g., displays) • Displays • Rely on industry R&D for hardware and many aspects of software
13. Computational Fluid Dynamics	• Validation of CFD codes • Unsteady aerodynamics • Submarine design • High-performance rotorcraft • Hypersonic flight • Propulsion system internal flows • Interdisciplinary CFD	◕	• Employ commercially available computing hardware for military systems and weapons
14. Air-Breathing Propulsion	• Aerothermodynamics • High-temperature and lightweight materials and coatings • Lightweight structural design • High-pressure ratio compression systems • High-temperature combustors and turbines • Reduced signature, multifunctional nozzles	●	• DoD R&D leads national efforts to provide the basis for future generations of aircraft gas turbine engines

(Continued)

Key: ● DoD/DoE R&D leads the US effort--DoD/DoE applications drive the technology ◕ DoD/DoE R&D comparable to industry and other agencies--many non-defense applications ○ DoD/DoE heavily reliant on industry or other agency R&D--non-defense applications dominate

Table C-1. Summary of Critical Technology Challenges (Concluded)

Technology	Technology Challenge	Defense Role	
15. Pulsed Power	• Compact high-power sources • Power conditioning • Power switching	●	• DoD and DoE developing all aspects of the technology
16. Hypervelocity Projectiles	• Projectile design • Projectile propulsion • Projectile-target interaction	●	• DoD and DoE developing all aspects of the technology
17. High-Energy Density Materials	• Insensitive energetic materials • Low-signature, low-hazard, reliable missile propulsion • Non-toxic propulsion for space application • Low-signature, low-vulnerability gun propulsion • Explosives for enhanced blast, fragment energy, and bubble energy for increased lethality warheads and torpedoes, and shaped charge jets for armor penetration	●	• DoD and DoE leading US R&D effort
18. Composite Materials	• Ultra-high-temperature metal, carbon, and ceramic matrix composites • Exterior and reinforcement coatings • Aerothermal responsive and life cycle effects	●	• DoD lead in R&D of life cycle effects on composites • Transition commercial technology to military platforms/systems
19. Superconductivity	• HTS materials and processing • LTS applications • Integration with semiconductors	●	• Lead US effort in R&D of high-temperature superconductors • Evaluate applications of low-temperature superconductors
20. Biotechnology Materials and Processes	• Materials • Processes • Sensors	○	• Evaluate DoD applications of industry and other agency R&D

Key: ● DoD/DoE R&D leads the US effort--DoD/DoE applications drive the technology ● DoD/DoE R&D comparable to industry and other agencies--many non-defense applications ○ DoD/DoE heavily reliant on industry or other agency R&D--non-defense applications dominate

Appendix D

GLOSSARY

GLOSSARY

A	Amperes
AAAM	Advanced Air-to-Air Missiles
A/cm	Amperes per centimeter
Ada	Name of DoD Higher-Order Language
ABF	Advanced Bomb Family
ACM	Advanced Conventional Munitions
A/D	Analog-to-Digital
AFV	Automatic Fire Control
AHWAS	Advanced Helicopter Weapon System
AI	Artificial Intelligence
AIA	Aerospace Industries Association
AJ	Anti-Jam
AJ/LPI	Anti-Jam/Low Probability of Intercept
ALCM	Air-Launched Cruise Missile
Al Ga As	Aluminum Gallium Asenide
ALVEY	Advanced Information Technology Program (UK)
AMRAAM	Advanced Medium Range Air-to-Air Missile
AOTH	Advanced Over-the-Horizon (Radar)
APC	Armored Personnel Carrier
ARI	Army Research Institute
ARM	Antiradiation Missile
ASAT	Anti-Satellite
ASIC	Application Specific Integrated Circuit
ASMD	Anti-Ship Missile Defense
ASRAAM	Advanced Short Range Air-to-Air Missile
ASW	Anti-Submarine Warfare
ATA	Advanced Tactical Aircraft

ATBM	Anti-Tactical Ballistic Missile
ATC	Automatic Target Cueing
ATD	Advanced Technology Demonstration
ATF	Advanced Tactical Fighter
ATR	Automatic Target Recognition
AUTO-SPEC	Automated Sensor/Processor Center
AWACS	Airborne Warning and Control System
BAP	Biotechnology Action Program
BiCMOS	Bipolar Complementary Metal Oxide Semiconductor
bit	Binary Digit
BMS	Battlefield Management System
BPS	Bits per Second
BTI	Balanced Technology Initiative
C^2	Command and Control
C^3	Command, Control, and Communications
C^3I	Command, Control, Communications, and Intelligence
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CAT	Computerized Axial Tomography
CB	Chemical/Biological
CBW	Chemical/Biological Warfare
CBD	Chemical and Biological Defense
C/C	Carbon-Carbon
CCD	Camouflage, Concealment, and Deception
CD ROM	Compact Disc Read Only Memory
CFD	Computational Fluid Dynamics
CL-20	A High Explosive Material
CM	Countermeasure
CMC	Ceramic Matrix Composite
CMOS	Complementary Metal Oxide Semiconductor
CNC	Computer Numerical Control
CPB	Charged Particle Beam
CRAY	A Superconductor Firm

CVD	Chemical Vapor Deposition
CW	Continuous Wave
DA	Department of the Army
DARPA	Defense Advanced Research Projects Agency
db	Decibel
DC	Direct Current
DEW	Directed Energy Weapon
DFLRV	German Aerospace Research Establishment
DIA	Defense Intelligence Agency
DNA	Defense Nuclear Agency
DoC	Department of Commerce
DoD	Department of Defense
DoE	Department of Energy
DRAM	Dynamic Random Access Memories
DRG	Defense Research Group
DU	Depleted Uranium
E-beam	Electron beam
ECCM	Electronic Counter-Countermeasures
ECG	Electrocardiogram
ECM	Electronic Countermeasures
EIA	Electronic Industries Association
EL	Electroluminescent
ELF	Extremely Low Frequency
ELINT	Electronic Intelligence
EM	Electromagnetic
EMI	Electromagnetic Interference
EML	Electromagnetic Launch
EMP	Electromagnetic Pulse
EMR	Electronic-Combat Multifunction Radar
EO	Electro-Optical
EOTDA	Electro-Optical Tactical Decision Aids
EPA	Environmental Protection Agency
ERINT	Extended Range Interceptors
ERIS	Exo-Atmospheric Re-entry Vehicle Interceptor System

ESG	Electrically Supported Gyroscope
ESM	Electronic Support Measures
ESPRIT	European Strategic Program for Research in Information Technology
ET	Electrothermal
EUCOM	European Command
EUREKA	European Research Koordination Agency
Europtica	European Optical Professional Society
EW	Electronic Warfare
FAA	Federal Aviation Administration
FAE	Fuel Air Explosive
FDA	Food and Drug Administration
FEL	Free Electron Laser
FLIR	Forward-Looking Infrared
FLOPS	Floating Point Operations per Second
FLOT	Front Line of Troops
FOG	Fiber Optic Gyro
FOG-M	Fiber-Optic-Guided Missile
FOS	Fiber Optic Sensor
FOSS	Fiber Optic Sensor System
FPA	Focal Plane Array
FRG	Federal Republic of Germany (West Germany)
FSED	Full-Scale Exploratory Development
G	Giga (billion)
g	Gram
g	Unit of acceleration equal to acceleration due to earth's gravitational field
(Ga, In) As	Gallium Indium Arsenide
GaAs	Gallium Arsenide
GB	Gigabyte
GBI	Ground-Based Interceptor
Gbit	Gigabit
GeV	Gigavolt
GHz	Gigahertz
GOCO	Government Owned, Contractor Operated

GOPS	Gigaoperations per Second
GVSC	Generic VHSIC Spaceborne Computer Program
HBR	High By-pass Ratio
HBT	Heterojunction Bipolar Transistor
HCl	Hydrochloric Acid
HCT	Mercury-Cadmium-Telluride
HE	High Energy
HED	High-Energy Density
HEDI	High Endo-Atmospheric Defense Interceptor
HEDM	High-Energy Density Materials
HEMT	High Electron Mobility Transistor
HF	High Frequency
HMX	A High Energy Material
HNHAA	A High Explosive Material
HP	Horse Power
HPM	High Power Microwaves
HRR	High-Range-Resolution
HSCT	High-Speed Civil Transport
HTS	High-Temperature Superconductor
HVG	Hypervelocity Gun
HVP	Hypervelocity Projectile
IBC	Impurity Band Conduction
IC	Integrated Circuit
ICBM	Intercontinental Ballistic Missile
ICI	Imperial Chemical Industries
ID	Identification
IEEE	Institute for Electrical and Electronics Engineers
IEW	Integrated Electronic Warfare
IFOG	Interferometry Fiber Optic Gyro
IGV	Inlet Guide Vanes
IHPTET	Integrated High-Performance Turbine Engine Technology
IM	Insensitive Munition
IMU	Inertial Measurement Unit
InP	Indium Phosphide

IR	Infrared
IR&D	Internal Research and Development
IRFPA	Infrared Focal Plane Array
IRST	Infrared Search and Track
ISAR	Inverse Synthetic Aperture Radar
ISDN	Integrated Services Digital Network
J	Joule
JANNAF	Joint Army-Navy-NASA-Air Force
$J_c(H)$	Critical Current (as a function of magnetic field) that can be Supported by a Superconductor
JDL	Joint Directors of Laboratories
JESSI	Joint European Submicron Silicon Program
JJ	Josephson Junction
k	Kilo (thousand)
kA	Kiloampere
kA/cm^2	Kiloamperes Per Square Centimeter
Kbit	Kilobit (one-thousand bits)
KEW	Kinetic Energy Weapon
kg	Kilogram
KGB	Soviet State Security Services
KHz	Kilohertz
km	Kilometer
kV	Kilovolt
kW	Kilowatts
LADAR	Laser Distance and Range (Laser Radar)
LAN	Local Area Network
LANL	Lost Alamos National Laboratory
LAP	Loading, Assembly and Packout
LCC	Life Cycle Cost
L/D	Length-to-Diameter Ratio
LEAP	Light-Weight, Exo-Atmospheric Projectile
LHX	A Helicopter Program
LLNL	Lawrence Livermore National Laboratory

LO	Low Observable
LPI	Low Probability of Intercept
LSI	Large Scale Integration
LTS	Low-Temperature Superconductor
LWIR	Long Wavelength Infrared
M	Mega (million)
m	Meter
m	milli (10^{-3})
MA	Mega-ampere
MAD	Magnetic Anomaly Detector
MBE	Molecular Beam Epitaxy
Mbps	Megabits per Second
MCC	Microelectronics and Computer Technology Corporation
MCT	MOS Controlled Thyristor
MESFET	Metal Semiconductor Field Effect Transistor
MeV	Million Electron Volts
MFLOPS	Million Floating Operations Per Second
MHD	Magnetohydrodynamic
MHz	Megahertz
MICRON	Micrometer (1 millionth of a meter)
MIMIC	Microwave and Millimeter-Wave Monolithic Integrated Circuit
MIPS	Million Instructions per Second
MITI	(Japanese) Ministry of International Trade and Industry
MMC	Metal Matrix Composite
MME	
MMW	Millimeter-Wave
MOCVD	Metal-Organic Chemical Vapor Deposition
MOG	Micro-Optic Gyros
MOMBE	Metal-Organic Molecular Beam Epitaxy
MOPS	Million Operations per Second
MOS	Metal Oxide Semiconductors
MOU	Memorandum of Understanding
mph	Milers per Hour
m/s	Meter per Second

MSI	Medium Scale Integration
MTAP	Multi-functional Target Acquisition Processor
MV	Megavolts
MW	Megawatts
MWIR	Mid Wavelength Infrared
NASA	National Aeronautics and Space Agency
NASP	National Aerospace Plane
NATO	North Atlantic Treaty Organization
Nb	Niobium
NCTR	Noncooperative Target Recognition
Nd:Yag	Niodinium: Yttrium Aluminum Garnet
NDE	Nondestructive Evaluation
NIST	National Institute of Science and Technology
NLU	Natural Language Understanding
nmi	Nautical Mile
NPB	Neutral Particle Beam
nsec	Nanosecond
NSF	National Science Foundation
NSIA	National Security Industrial Association
NTIS	National Technical Information System
OASYS	Obstacle Avoidance System
OCCAM	Programming Language developed by UK
OEIC	Optoelectronic Integrated Circuits
OGV	Compressor Outlet Guide Vanes
OIP	Optical Information Processing
OITDA	Optoelectronic Industry and Technology Development Association
ORNL	Oak Ridge National Laboratory
OS	Operating System
OSTP	Office of Science and Technology Policy
OTH	Over the Horizon
P&E	Propellants and Explosives
PCB	Polychlorinated Biphenols
PCSS	Photo-Conductive Semiconductor Switches

PEEK	A high temperature thermoplastic
PFN	Pulse Forming Network
PIP	Product Improvement Program
PLC	Pulse Inductor/Capacitor
PMC	Polymer Matrix Composites
PRC	Peoples Republic of China
PRF	Pulse Repetition Frequency
PROFS	Prototype Regional Observing and Forecasting System
PtSi	Platinum Silicide
Q-value	A Term Referring to the Quality of a Radio Frequency Receiver
R&D	Research and Development
RAM	Radar Absorbing Materials
RCS	Radar Cross Section
RCV	Remotely Controlled Vehicle
RDTE	Research, Development, Test and Evaluation
RDX	A High Energy Material
RF	Radio Frequency
RFOG	Resonant Fiber Optic Gyro
RH32	Radiation-hardened 32-bit
RISC	Reduced Instruction Set Computer
RLG	Ring Laser Gyro
RSRE	Royal Signals and Radar Establishment
RST	Rapid Solidification Technology
RSTA	Reconnaissance, surveillance, and target acquisition
RV	Re-Entry Vehicle
RWR	Radar Warning Receiver
s	Second
S&T	Science and Technology
SADARM	Search and Destroy Armor
SAM	Surface-to-Air Missile
SAR	Synthetic Aperture Radar
SBI	Space-Based Interceptor
SBIR	Small Business Innovative Research

SC	Superconductor
Scramjet	Supersonic combustion ramjet
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SDS	Strategic Defense System
SEI	Software Engineering Institute
Sematech	Semiconductor Manufacturing Technology
SFC	Specific Fuel Consumption
SFW	Sensor-Fused Weapon
SHS	Self-Propagating High-Temperature Synthesis
SIGINT	Signal Intelligence
SIMNET	Simulation Network
SKEP	Super Kinetic Energy Penetrator
SLM	Spatial Light Modulator
SMES	Superconducting Magnetic Energy Storage
SNPE	Societe Nationale de Propulsion et Energetiques
SOI	Silicon-on-Insulator
SOS	Silicon-on-Sapphire
SPC	Software Productivity Consortium
SQUID	Superconducting Quantum Interference Device
SRAM	Static Random Access Memories
SRT	Strategic Relocatable Targets
STARS	Software Technology for Adaptable, Reliable Systems
STOL	Short Take-Off and Landing
STOVL	Short Take-Off and Vertical Landing
SW	Smart Weapon
SW/ATR	Smart Weapon/Automatic Target Recognition
SWIR	Short-Wave Length Infrared
2D/3D	two-dimensional/three-dimensional
T	Tera (10^{12})
T_c	Critical Temperature Below Which a Material Becomes a Superconductor
TCE	Tetrachloroethylene
TOPS	Thousand Operations per Second

TMP	Tele-Operated Mobile Platform
TNT	A High Energy Material
T/R	Transmit/Receive
TREE	Transient Radiation Effects in Electronics
TSMD	Time Stress Measurement Device
TTCP	The Technology Cooperation Program
TWT	Traveling Wave Tube
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UHF	Ultra-High Frequency
UK	United Kingdom
USDA	US Department of Agriculture
USSR	Union of Soviet Socialist Republics
UUV	Unmanned Underwater Vehicle
UV	Ultraviolet
VCR	Video Cassette Recorder
VHDL	Very high speed integrated circuit hardware description language
VHF	Very High Frequency
VHSIC	Very High Speed Integrated Circuits
VLSI	Very Large Scale Integration
VLWIR	Very Long Wavelength Infrared
V/STOL	Vertical or Short Take-Off and Landing
VTOL	Vertical Take-Off and Landing
WORM	Write Once Read Many
WP	Warsaw Pact
WPC	Warsaw Pact Countries
WRD&T	Weapons Research Development and Test
WRM	Wide-Area Mine
III-V Compound	A compound material consisting of elements from columns III and V of the Periodic Table of Elements.
II-VI Compound	A compound material consisting of elements from columns II and VI of the Periodic Table of Elements.
2D	Two-dimensional
3D	Three-dimensional

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The second Annual Defense Critical Technologies Plan responds to the requirement that the Secretary of Defense submit to the Committees on Armed Services of the Senate and House of Representatives an annual plan for developing the technologies considered by the Secretary of Defense and the Secretary of Energy to be the technologies most critical to ensuring the long-term qualitative superiority of the United States weapon systems. The report selects 20 critical technologies. The selection process is described, criteria for selection are set forth, and industrial and international assessments are summarized. The major portion of this report is contained in 20 sections in Appendix A, one section for each critical technology. Each section addresses the questions posed by Congress on funding, plans and milestones, industrial base and manufacturing issues, and the competitiveness of US industry; it also provides an assessment of the positions of the Soviet Union, NATO, Japan and other industrialized countries in niche technologies within each critical technology. Keywords, DE

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